Abstract

This article introduces a virtual reality system for upper limb motor rehabilitation of patients after stroke. The system is based on a therapeutic approach that uses visual illusions of movement activity to foster motor learning. Abstract visualizations that continually change according to the patients' upper limb positions are displayed. At the same time music is also played and used as input for the visualizations. During the interaction patients move freely to explore the virtual environment. To aid motor learning, the healthy limbs' movements can be mirrored and manipulate the visual effects on the affected side, thus establishing the impression of unrestricted motor behavior. Presence is identified to be a defining aspect of this approach. Specifically it is assumed that the level of perceived presence during the intervention correlates with the therapeutic outcome.

A prospective, controlled pilot study was carried out to test for effects of treating patients after stroke with the system. 5 patients used the system on a daily basis for five days. A set of clinical measurements was applied pre- and post-test and presence was evaluated after each session. The system was applicable and all patients improved their motor function moderately. 3 patients experienced a strong sense of presence.

The results of the study support the above assumption. However, the broad range of reactions to the intervention indicates a need to individually tailor the system to the patients' capabilities. This work points to the importance of considering the presence research perspective for the development of virtual rehabilitation systems.

Keywords (max. 6): virtual reality; presence; virtual rehabilitation; stroke; motor learning

Words (max. 250):

Introduction

In recent years virtual reality (VR) has been used to treat patients with motor disorders after stroke (Saposnik & Levin, 2011). Available systems provide playful environments in which the patients, through the use of motion tracking devices, interact with an avatar using natural movements. The virtual worlds include game components and are designed so that patients need to perform therapeutically relevant movements to achieve goals and to level up. A recent review of 19 clinical studies testing different VR systems for upper and lower limb rehabilitation after stroke testifies to a small advantage over traditional treatment, yet it was stated that further research with more specific patient groups and well defined therapy systems is needed to validate the results (Laver et al., 2012).

There is no clear, one-for-all approach to virtual rehabilitation. Rather, patients react to the systems in varied ways not only based on their particular disorder, but also based on their personality traits. Just like in computer games, what motivates one might bore another. Since the motivational factor is a major reason to introduce VR technology in this field, systems should be individually tailored. Just which parameters of a virtual world are suited for which particular group of patients is unknown (Laver et al., 2012). The presence research perspective provides a ground for investigations in this direction. Though this has been stated before (Weiss & Klinger, 2009), few studies have taken the perspective.

Presence for neurological rehabilitation

Presence (i.e. the perceptual illusion of nonmediation (Lombard et al., 1997)) is of special interest for the neurological rehabilitation after stroke, since it can provide theoretical insight for a number of treatment approaches. In the so-called mirror therapy, patients with hemiparesis experience a visual illusion of a moving limb (Ramachandran & Altschuler, 2009). They sit in front of a mirror and the position is such that the image of their healthy limb is superimposed over their affected limb. The patients are then instructed to perform symmetric movements while watching into the mirror. The reflection initiates the kinesthetic impression of a moving limb on the affected side.

VR can be used to replace the mirror (Eng et al., 2007; Gaggioli et al., 2006). Avatar limbs are displayed and controlled accordingly by the patients using solely the movement of the healthy limb. It has been shown that motor recovery after stroke benefits from mirror therapy (Thieme et al., 2012) and that virtual mirroring can contribute similarly (Dohle et al., 2011). For the therapeutic effect of this approach the self-attribution of the illusory limb on the affected side seems to be important (Thieme et al., 2012).

Presence is defined as the perceptual illusion of non-mediation (Lombard et al., 1997). When presence is high, sensations that are artificially generated (e.g. using a mirror or VR) are perceived as real and the subject fails to acknowledge the role of the technology in the experience. The self-attribution of an illusory limb conceptually corresponds to this definition of presence.

Riva et al. introduced a cognitive model of presence and described its role in producing controlled motor actions within an external world (Riva et al., 2010). In this model, presence is linked to the subject's capacity of enacting all its motor intentions. Stroke patients with hemiparesis would consequently experience a low sense of presence regarding their paretic side, but this experience can be restored through the mirror illusion.

In this work, it is assumed that the therapeutic effect of the mirror illusion increases when the presence experience is high. This assumption formed the basis for the development of a system for upper limb motor rehabilitation after stroke. A pilot study that applied the system was tested. In the following section of this paper, the system is introduced. Then the pilot study and the results are described. Finally, in the discussion, a perspective for further investigation is posed. This work points to the importance of considering the presence research perspective in the development of virtual rehabilitation systems.

AVUS rehabilitation system

The AVUS system (short for 'abstract virtual environment for stroke therapy') utilizes abstract and fictive visualizations of human upper body movements (see figure 1) to foster exercise and motor learning after a stroke. The patients' movements are captured with a Microsoft Kinect sensor and transformed using the Processing framework (processing.org) to generate aesthetic visuals with different levels of abstraction. During therapeutic intervention with this system, patients experience the illusion of control over their paretic side and train their upper limb motor abilities.

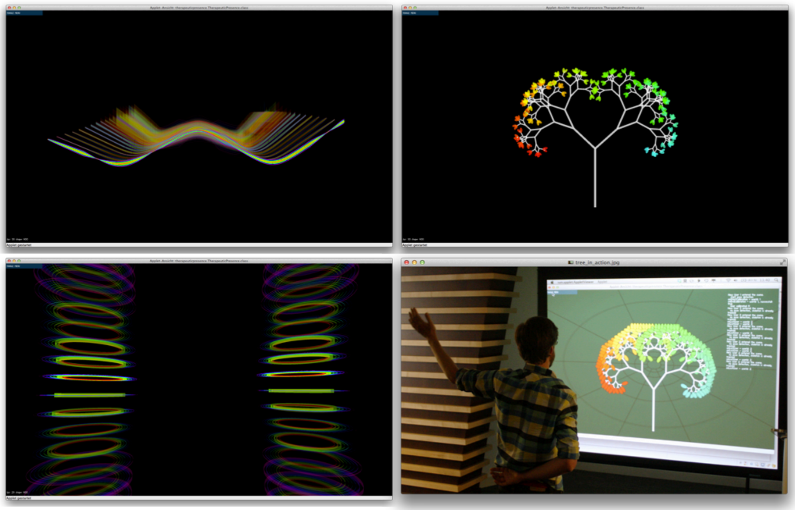

Figure 1: The different visualization types of the AVUS system and its application

Design rationale

As previously mentioned, this research assumes that a strong experience of presence regarding the affected body side is supportive for the rehabilitation of hemiparesis after stroke. In order to allow for this experience and to be able to analyze it, a design was chosen that made use of upper limb movement visualizations with different levels of abstraction.

In theoretical analyses of presence it was stated that the experience is not primarily related to the visual realism of an environment, but that it is rather the user's ability to enact all intentions for afforded actions within the environment that contributes to it (Regenbrecht & Schubert, 2002; Riva et al., 2010). A realistic environment affords actions that are based on the individual experiences with the reality and it is therefore sheer impossible for a developer to foresee all intentions a user of such an environment can have. On the other hand, an abstract and fictive environment affords only actions that are based on the experiences with the system itself. The limitations of the system are clearly visible and after a phase of exploration, the intentions of the users will be narrowed to what the environment allows for. Therefore, it is much easier to provide sufficient control mechanisms for the according actions and presence may constitute easier.

Contemporary media art makes use of the explorative nature of abstract and fictive virtual environments, as well. Often, the resulting work is regarded as highly immersive. A field of media art that is particularly well suited to be used for virtual rehabilitation is called *Generative Design*. This field makes use of algorithms that are based on simple mathematical rules to transform a given dataset into a visual representation. The representation then displays certain information of the dataset in an accessible and artistic fashion. Such transformations can be used in an interactive environment, too, e.g. to visually enhance a dance performance (Chunky Move, 2006).

System description

Using the Generative Design approach the AVUS system transforms the movement data of the patients into abstract visualizations. An auditory component was also considered, as coherent signals on multiple sensory channels within a virtual environment add to the presence experience (Lombard et al., 1997). Furthermore, music has been shown to foster movement activity (Spitzer, 2002). Therefore, music is played during the AVUS therapy and used as input to manipulate the visualizations, too. By combining these aspects, an explorative and artistic atmosphere that allows for a high degree of presence is generated.

In a first version of the system, three different visualizations that gradually distinguish from human upper limb representations are implemented (see figure 1). The *Waveform Visualization* assigns the position of the patient's elbow and wrist joints in relation to their respective shoulder joints onto a Bezier curve, which at the same time displays samples of the background music. The *Generative Tree Visualization* uses a mathematical tree graph, which is recursively drawn using the flexion angles of the shoulder and elbow joints. The music properties affect the stroke width and the orientation of the tree leafs. Finally the *Ellipsoidal Visualization* displays column structures that are arranged according to the position of the patient's hands. Here, the flexion angles of the joints affect the radius and the orientation of each structure and the spectrogram of the music defines the stroke widths of the colored orbit ellipsoids.

Continuous interaction with these visualizations is provided meaning that every movement results in an immediate visual effect. There are no pre-defined goals that externally structure the interaction. Rather, the patients explore their possibilities to produce various shapes in a self-directed manner. At the same time, they exercise at their limits of motion.

A distinct mode of operation applies the above described mirror therapy principle. In this mode, only the movements of the unaffected body side are captured and then used to manipulate both sides of the visuals. The results will always be symmetric and an illusion of bilateral movement will be established for the patient.

The AVUS-system was developed in close contact with patients and clinicians in three rehabilitation centers. Beta tests of early prototypes asked for informal feedback and the information was used for further development. In these tests the system proved to be applicable.

Pilot study

The effects of training with the AVUS system for motor rehabilitation of patients with hemiparesis after a stroke were tested in a pilot study that followed a prospective, controlled case-series design. The studied intervention protocol derived from the aforementioned beta tests. A set of measurements was applied to check for effects on a broad basis. The goal was to establish detailed knowledge about possible therapeutic effects of the AVUS system and to investigate the interplay of defining aspects of the intervention.

As described above, presence was one such defining aspect. Another aspect came from the general neurologic rehabilitation approach. The mirror therapy builds on the kinesthetic impression of movement on the affected side. This impression is externally triggered, but the vividness is also dependent on the patients' individual ability to accurately imagine movements (Dettmers & Nedelko, 2012). Thus the so-called motor imagery ability was evaluated. Finally the self-directedness of the intervention stands out conventional therapeutic protocols. During the AVUS therapy, the patients perform movements according to their personal capabilities and produce appealing visuals. It was assumed that the possibility to express themselves at their own self-chosen level influenced the patients' subjective judgment of the rehabilitation outcome and they were therefore asked to rate it.

The study was performed in accordance with the ethical principles outlined in the Helsinki declaration of the World Medical Association (WMA, 2008), however approval of an ethical committee was not obtained due to the prospective nature of the study.

Participants

Participants in the study were hemi-paretic patients in the sub-acute and chronic phase after stroke showing at least minimal proximal arm function as well as stable posture control. The therapy could be performed standing or sitting. Excluding criteria were visual impairments, strong cognitive impairments, dementia, global aphasia and epilepsy. The recruitment and the study took place in a neurological rehabilitation center that specialized in stroke care. All participants were in-patients receiving an individually focused therapy program.

8 patients (mean age 67, demographic data see table 1) fulfilled the criteria, gave informed consent and were tested in two runs of the study. The patients were randomized into two groups, one experimental group (EG, 5 patients) who received the intervention with the AVUS system and one control group (CG, 3 patients) who received a control intervention. Patients as well as raters were blind to this administration. Because of the prospective research interest more patients were allocated in the EG. Balance of groups according to base-

line motor function was assured. All patients completed the study, however one patient had to be excluded from analysis due to a fall accident.

Intervention protocol

The patients in the EG trained with the AVUS-system on a daily basis. With the same intensity the patients in the CG received unspecific upper-limb movement training while concentrating on background music. A physiotherapist administered both treatments. The procedure for the EG followed three phases.

In the first phase, the patients observed the visualizations of prerecorded movements and mentally imagined performing the corresponding movements. This phase was meant to tune into the unfamiliar approach. In the second phase, the patients explored the three visualizations for 90 seconds each while operating the system with both upper body sides. The instructions were to try symmetric movements as good as possible, but to otherwise move freely. The third phase utilized the mirror-therapy-mode in the exact same progression. This time the visualizations were always perfectly symmetric and the illusion of correct movement on the affected side was established. This mode aimed to enhance motor learning.

Between all phases, short relaxation breaks took place. Both groups received their treatment for approximately 30 minutes on 5 successive days in addition to their usual rehabilitation program.

Measurements

Motor function was assessed using the Fugl-Meyer assessment upper extremity (FMA-UE). The FMA-UE proved high reliability (inter-rater: r>0,984; intra-rater: r>0,995; (Duncan et al., 1983)) and construct validity (Hsieh et al., 2009) and is used extensively within the stroke population. The motor imagery ability (MIA) was assessed using the NOI Recognise left-right-discrimination of hand images (Moseley et al., 2012). Such discrimination tasks have been used with hemiplegic stroke patients and a relation between the accuracy and the speed of the rating with the motor imagery ability has been established (Johnson et al., 2002). Both these measurements were applied pre and post intervention. The patients' subjective judgment of the therapeutic outcome was evaluated post intervention using a colored analog scale (CAS). Analog scales have frequently been used in clinical research to ask for subjective ratings (McDowell, 2006). One physiotherapist who was blind to the group allocation of the patients performed these measurements.

In addition to the above measures the patients in the EG were asked for their presence experience following each intervention session using a modified version of the Igroup Presence Questionaire (IPQ). The IPQ comprises three presence dimensions (spatial presence, involvement, realness) and one general rating. It was developed from a combination of established questionnaires as well as additional items and initially tested in two studies with N=246 and N=296 (Schubert, 2003). It showed high internal consistency (α>0,63) and the dimensions are regarded as independent factors. 14 items are rated on a 7-point Likert scale between respective anchors. A German version of the questionnaire was available. For the pilot study the items regarding the realness dimension were excluded because due to the obvious non-realness of the AVUS they were thought to confuse the patients and the general aim was to reduce the cognitive load of the questionnaire as much as possible.

Interviews asking EG patients for their experience with the AVUS therapy were conducted on the last day of the intervention. The data of the interviews will be analyzed within an upcoming article.

Results

The study took place in March and April 2013. All organizational procedures were successful and the technological installation was reliable. Generally the AVUS therapy was applicable in the clinical context. Figure 2 shows impressions from the EG intervention.

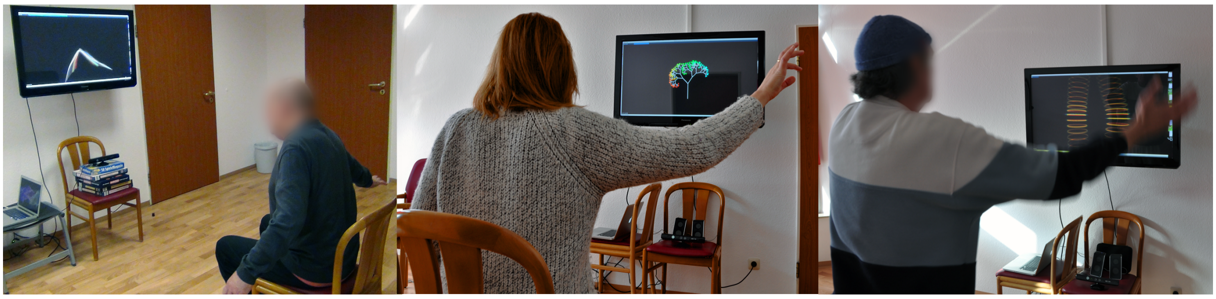

Figure 2: Impressions from the experimental group intervention using the AVUS system

Table 1 gives an overview of the recorded data for all patients. Basic demographic data is displayed. Age range was broad from 50 to 85. Only one participant was female. Sides of the hemiparesis were balanced overall and within groups. Stroke onset varied from 1 to 7 months before participation in the study.

	experimental group					**control group**	
Measurement	**SC**	**RI**	**RE**	**HG**	**NE**	**KE**	**WE**
age/sex	51 / f	72 / m	50 / m	75 / m	68 / m	55 / m	85 / m
aff. side/onset	L / 6mo	R / 3mo	L / 1mo	R / 3mo	L / 1mo	R / 7mo	L / 1mo
FMA-UE				*EG diff $\bar{x}$: 3±1.6*		*CG diff $\bar{x}$: 5±1.4*	
pre	13	10	15	49	29	42	17
post	18	11	18	51	33	48	21
diff	5 (38%)	1 (10%)	3 (20%)	2 (4%)	4 (13%)	6 (14%)	4 (23%)
MIA rating				*EG median: 1*		*CG median: 1.5*	
mean pre/post	2	1	1	-2	0	3	0
CAS				*EG $\bar{x}$: 6.7±3.3*		*CG $\bar{x}$: 7.3±1.4*	
post	8.1	1.0	9.5	7.6	7.4	8.3	6.3
IPQ							
general pres	5.8	0.0	5.8	5.8	1.2		
spatial pres	4.8	1.1	4.9	4.8	2.1		
involvement	6.0	0.6	5.7	2.8	1.5		
mean	5.5	0.6	5.5	4.5	1.6		

Table 1: Quantitative results of the pilot study

The pre and post results of the FMA-UE are shown. The difference was calculated in absolute and relative (to the pre test) values. Group mean values and standard deviations are displayed. Pre test baseline measures deviated considerably from 10 to 49 (FMA-UE max 66). All patients improved their functional capabilities within a comparable range (+1 to +6). However, relative improvements are clearly distinguishable (+4% to +38%). The patients in the CG improved their motor function more (mean +5) compared to the patients in the EG (mean +3).

MIA was developed by rating the accuracy and speed results from the left-right discrimination task. Mean values of the pre and post tests were used and compared against healthy subjects' standard values (Moseley et al., 2012). Each item (accuracy, speed, speed difference left/right) contributed -1 (bad performance), 0 or +1 (good performance) to the accumulated MIA score ranging from -3 (very bad) to +3 (very good). The group's median scores are shown. Individual capabilities deviated considerably (range: -2 to +3) and MIA was less pronounced in the EG (median +1) compared to the CG (median +1.5).

The CAS judgment was transformed to a numerical value by a metric measurement of the distance to the zero position of the scale. The scale length was 10 cm, therefore values range between 0.0 (very bad) and 10.0 (very good). Group mean values and standard deviations were calculated. Most individual judgments of therapeutic outcome were placed well in the upper half of the scale (>6.3) except for one participant of the EG (1.0). This outlier contributed over proportional to the EG's mean value (6.3) that is lower than for the CG (7.3).

The results of the IPQ are the mean values of the five post-intervention assessments and correspond to the above-mentioned presence dimensions. Additionally, the overall mean values were used for a combined presence rating. IPQ results are only available for the EG. Three patients experienced strong presence (mean >4.5) while two patients experienced low presence (mean <1.6). All dimensions contributed equally to these results and they were strongly correlated ($r_{GP,SP}$=.99, $r_{GP,INV}$=.86, $r_{SP,INV}$=.86).

Correlations between measurements were performed to explore the interplay of defining aspects of the therapeutic approach. For all possible combinations Spearman's rho (ρ) and Pearson's correlation coefficient (r) were calculated. Figure 3 displays those correlations that were found to exhibit substantial information. Due to the small sample size, reliable significance tests could not be carried out.

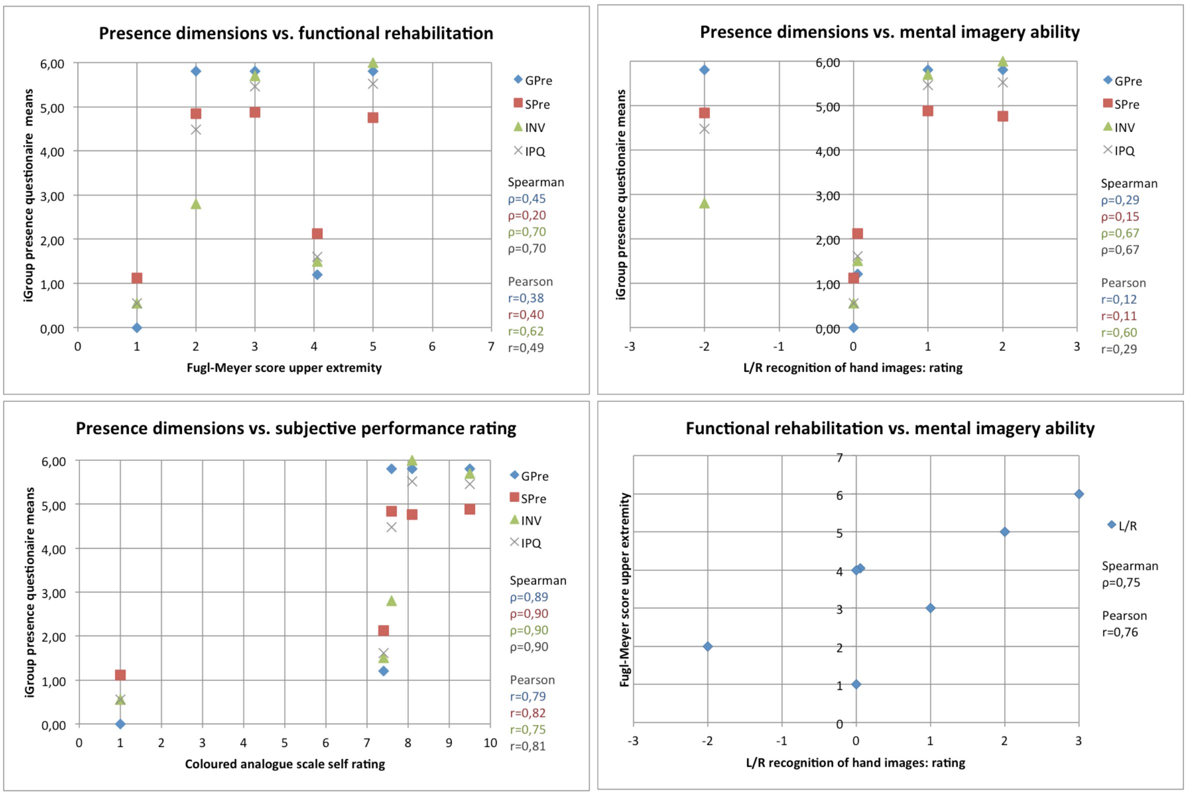

Figure 3: Substantial correlations between measurements.

The experienced presence during the intervention was found to correlate with the functional outcome of the EG (ρ=.70, r=.49) and the involvement dimension contributed the most to this (ρ=.70, r=.62). Presence also correlated strongly with the subjective judgment of the therapeutic outcome (ρ=.90, r=.81). Here all dimensions contributed equally. The functional outcome correlated considerably with the mental imagery ability (ρ=.75, r=.76). However, presence only correlated moderately with this ability (ρ=.67, r=.29).

Discussion

The article presented the AVUS-system for upper limb rehabilitation of patients with hemiparesis after a stroke and described a prospective pilot study. Presence was a central aspect for the development of the system and the underlying therapeutic approach. It was assumed that a strong experience of presence during the intervention contributed to the therapeutic outcome. The results of the study support this assumption.

The overall benefit of the therapeutic approach cannot be proven statistically due to the prospective nature of the study and the small sample size. Patients who trained with the AVUS-system improved their motor function in a comparable range with regard to those who received a control intervention, but evidence need to be established in a continuing clinical study. However, no adverse effects were observed and a general applicability of the AVUS-system in the clinical context can be attributed. The correlation of measurements exhibited some trends.

Patients with high presence ratings in particular seemed to benefit from the intervention and this was especially pronounced for the involvement dimension. This suggests that a strong focus on the virtual environment helped to concentrate on the training. Interestingly, the experience of being somewhere else (termed spatial presence) was not as important. This indicates a mere motivating effect of the AVUS. However, a link between the presence experience and the therapeutic approach was established. Therefore continuing this research to investigate this link with greater detail seems promising.

Furthermore, a strong presence experience seemed to add to the patients' subjective impression of their upper limb motor improvement. This could indicate that the patients' activity during the intervention left the impression of success the more they felt present in the virtual world. Considering the importance of regaining self-confidence for patients suffering from a stroke, this personal judgment might reflect a contribution to the overall quality of life (QOL). Future research should therefore particularly focus on applying QOL outcome measures. Arguably the AVUS-system fosters the patients' rehabilitation on a broad scale.

In addition to the presence experience, another defining aspect of the intervention has been assumed to influence the therapeutic outcome. The ability to perform motor imagery differed considerably between patients and the training effect of both the EG and the CG intervention was high for those patients with a good mental imagination of movements. However, presence seemed to be independent from this ability. Although the majority of patients reported strong presence, indicating that abstract visualization can indeed establish this experience, the results clearly show that the AVUS-therapy is not suitable for all patients. Both these defining aspects develop over time, but they are also dependent on personality traits. Extending this line of research may gain detailed information about which group of patients the system is suited for.

This study was the first to test a virtual rehabilitation system, which was developed explicitly drawing on presence research. The sense of presence during the intervention was evaluated using a modified version of the IPQ and its application with stroke patients was feasible. The assessment has led to insights about the contribution of presence to two therapeutically relevant outcome measures, but further data is required to allow population-level conclusions. Additionally, a general dependence of virtual rehabilitation systems on the patients' individual capabilities was stated. This work points to the importance of considering the presence research perspective to develop individually tailored systems.

Future development will enhance the AVUS-system based on the experience from the pilot study. More types of abstract visualizations will be implemented to allow for longer lasting interventions. Interaction with the auditory component will be established such that the patients' movements may influence certain features of the music. Future investigations will evaluate the effect of the degree of abstractness on the presence experience. Finally, patients suffering from other diseases (e.g. chronic pain, movement phobia) will also be tested to investigate the benefits of the AVUS-therapy for their rehabilitation.

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