A Haptically Enhanced Painting as a Tool for Neurorehabilitation*

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Abstract – **This paper examines a new form of interaction combining haptic and sonic exploration with static visual information from a real painting. Motivated by recent work in neurorehabilitation exploring group interactions with a robot, and by the educational and explorative value of artefacts, we investigate the feasibility of an interactive painting as a potential tool for the rehabilitation of brain injuries. The study consisted of a series of thirty-six single case studies with healthy individuals exploring a painting through haptic feedback with/without sonic interaction and assessed using a multidimensional measurement intended to evaluate the participants' subjective experience. The results showed that participants engaged with the interactive installation and executed more movements while exploring the painting in pairs. It appears that the haptic painting paradigm encourages development of analytical skills, imagination, promotes spatial skills realisation and enhances touch/hearing sensory channels. The results suggest that this approach might be of value to neurorehabilitation by exploring concepts of augmented artefact installations with technology (haptics + sound), promoting social integration and potential use in public spaces.**

Keywords **– Social interaction, motivation, engagement, collaborative rehabilitation.**

I. INTRODUCTION

Maintaining motivation and attention levels while learning new motor skills or re-learning forgotten skills after neurological impairment, has been shown to have a positive impact on brain plasticity [1, 2]. Strategies for influencing behaviour in brain injury or cognitive impaired patients are needed, not only for therapy engagement but also for supporting appropriate levels of motivation essential for motor learning and generalisation of learning to occur. The assumption is that by providing individuals with motivating and challenging therapy at their convenience will result in longer therapy exposure, ultimately lowering impairment and disability. Such therapies must be delivered in a well-monitored and structured environment that is acceptable to the clinicians responsible for patient's recovery management.

Understanding the individual's goals is important as needs and motives often drive goals, influence behaviours and affect personal effort. Such needs might surface out of emotional, independence, and social goals that may be obstructed as a result of neurological impairment [3, 4]. It is suggested that the strength of the individual's needs very much depend on the individual's psychological disposition, their ability to cope, and on the recovery progression leading to residual deficits. Thus functional limitations prompt for stronger needs to be independent and engage in the community [3, 4].

Machine mediated therapies have already been introduced to the hospital environment with no harmful side effects to the patients and with positive results for some individual patients [5]. Strategies for increasing and maintaining patient interest vary. Some systems incorporate activities of the daily living such as car steering into the therapy paradigm [6] whereas other systems attempt to motivate patients via functional reaching and grasping [7]. Other studies [8, 9] propose to address the social exclusion problem by developing systems that provide cooperative tasks between patient and therapist and through collaborative play between individual patients and between patient groups [10]. This new concept of social rehabilitation can be expanded from small systems used in the home, to a combination of home systems and technological rehabilitation centers.

Recent work looking at interactions between stroke patients and companion robots has shown that it is possible to increase engagement at a task (e.g. moving books from one table top to another) when robots assume a coaching role (robot prompting for actions using simple beeping noises) rather than proving physical assistance [11].

Our recent work examining how group interactions reshape an individual's mental model while interacting with a sonic robot presents with opportunities to explore the dynamics of group collaborations in therapy [12].

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* This work was supported in part by the School of Science and Technology, Middlesex University, London.

The work presented in this paper explores further the concept of group interaction with possible benefits of engaging with artifacts, such as paintings, and creative expression or playful activity beyond the clinic or home scenario. Tapping into the social nature of art exploration, we investigate its potential as a contributor to enhancing sensory/emotional experiences, symbolic/emotional expression, cognitive development and social connectedness.

Previous systems have proposed using VR environments for training of painting and cooperative skills by mapping the 2D rendering of the virtual painting to the haptic world [13], [14]. Our system, in contrast with typical VR based haptic interaction, does not use dynamic visual cues mapping the haptic world. In our case, we use a real physical painting (not a VR representation), which prompts for some imagination to occur (in particular with spatial aspects) as users explore the visualized third dimension while performing three-dimensional movements aided by immersive haptic and sonic cues carefully designed to enhance the main elements in the paintings.

III. METHODS

A. *Study Design*

Thirty-six healthy subjects (aged between 18 and 65 years) (female 11, male 25) were recruited from Middlesex University, to conduct an experiment that involved interacting with two real paintings using a haptic device. The study consisted of a series of 36 single case studies and comprised two experiments. Twelve subjects were equally divided into two groups in experiment one (6 subjects per group) and twenty-four subjects were allocated to two groups in experiment two (12 subjects per group).

Experiments consisted of subjects exploring a painting through haptic feedback with/without sonic interaction while performing movements with the haptic device in three dimensions (Fig. 1) and are described as follows:

Experiment 1: Each group explored the ‘ball painting’ and was involved in two different phases:

a) Phase A, consisted of a subject exploring the ‘ball painting’ with haptic feedback while grasping the Novint Falcon robot.
b) Phase B, the subjects explored the ‘ball painting’ using haptic and sonic interactions while grasping the Novint Falcon robot.

Experiment 2: Two equally numbered groups explored the ‘water painting’ using haptic and sonic interactions while grasping the Novint Falcon robot. Subjects worked either alone or in pairs to interact with one painting using one Novint Falcon robot and were grouped as follows:

a) Singles, subjects interacted with the ‘water painting’ on their own.
b) Pairs, subjects interacted with ‘water painting’ while cooperating with another study participant. Cooperation here refers to the two subjects interacting with the painting together where they engaged in conversation and took turns to explore.

At the end of each experiment the study participants were asked to fill a questionnaire survey rating the experience. Subjects were randomized into one of the two phases in experiment 1 to see whether there were any differences or not in preference vs. expectancy related to the order of the phases. At all times each participant’s interactions were recorded by three different camcorders.

B. *System Description*

The experimental setup (Fig. 1 and 2) for this study consisted of a PC running Windows 7, a 3DOF Novint Falcon robot, a plinth (designed for the robot), two large speakers and a painting. The computer ran two separate applications (haptic application to generate and control haptic objects/effects and Max/MSP software to manipulate sounds) that communicated to each other via OSC (Open Sound Controller) messages. Two speakers were positioned to the left and right-hand sides of the user. The paintings represented a solid sphere (ball painting) for experiment 1 and a seaside-landscape (water painting) for experiment 2 (Fig. 1).

The environment was a dark room with a single light projected onto the painting (Fig. 2). The computer and researchers were hidden from user’s view. The robot was placed on the top of the plinth for the user to grab its end-effector and move freely (limited by the mechanical workspace of the robot - approximately 7.9×10^{-5} m^3).

Fig. 1 Subject exploring the painting in experiment 2. Left top: ball painting used in experiment 1. Left bottom: water painting used in experiment 2.

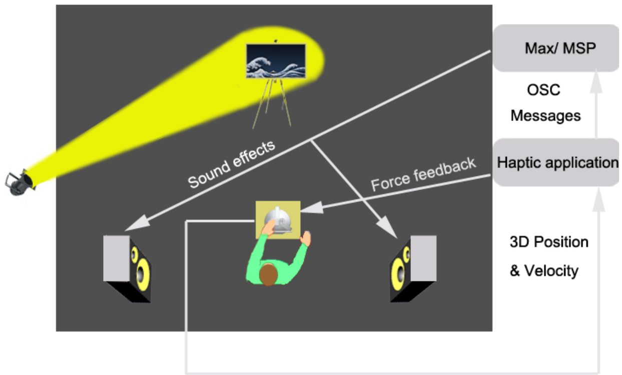

Fig. 2 Interactive painting experimental system. Subjects interact with the painting by grabbing and moving the Novint Falcon end-effector handle.

In experiment 1, a haptic sphere was modelled to represent the ‘ball painting’ and positioned in the centre of the haptic device’s workspace. Contact forces were generated based on collisions between the device's end-effector and the surface of the haptic sphere. Forces were rendered based on the God-object algorithm [15]. The God-object is defined as a virtual point that is not able to penetrate into hard surfaces. The position of the God-object is updated for every step of the haptic loop. A force generated by a mass-less spring simulation will stop the God-object moving through the surface of a rigid body if a haptic interface point (HIP) - where the God-object moves towards - penetrates into the body. The force F_S is given by Hooke's law as:

$$F_S = -k\Delta x = -k(x_{HIP} - x_{GodObject}) \tag{1}$$

Where k is the spring constant defining the surface's stiffness and Δx is spring's displacement.

In experiment 2, a virtual water environment was modelled using a velocity dependent spring-damper combination to simulate increased viscosity when the device's end-effector position moved under the water surface. As the movement velocity increased under the virtual water surface, the perceived effect was increased movement resistant. The algorithm uses Newton's second law to generate force feedback effects (mass-damper, spring-mass-damper and mass-acceleration) where a 0.6 maximum device damping was chosen to closely match the feeling of moving the hand under water. Table I summarises the algorithm used, adapted from the CHAI 3D library.

TABLE I

Algorithm: Water viscosity for Experiment 2

```
if position of end-effector < water level then
    Get max damping of haptic device
    Kv = 0.6 * max damping of haptic device
    Get device velocity vector
    Compute a scale factor [0,1] of percentage of tool volume
      immersed in the water
    Scalar = -Kv * scale
    Compute force damping by multiplying velocity vector by Scalar
    Force -> haptic device
end if
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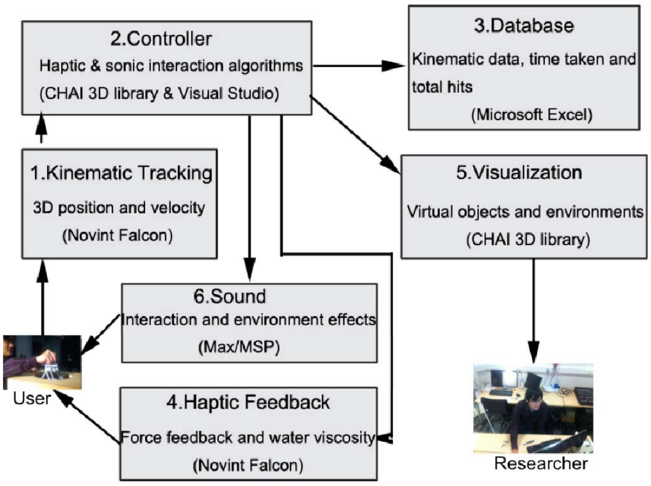

Fig. 3 System flowchart. The virtual objects and environments in visualization component were only viewed by the researcher.

Fig. 3 shows a flow chart for the interactive painting system developed. The sound effects were implemented using the Max/MSP software package. The haptic application was linked to Max/MSP via OSC messages that were sent/received using UDP protocol and Port number 8000 in a local network. The CNMAT plug-in for Max/MSP was used to receive all OSC messages that were sent from haptic application. Every time a subject hit the ball or water surface, the haptic application sent different signals to Max/MSP, which in turn generated various sounds depending on the position and velocity of the device end-effector. A Pan plug-in was added in Max/MSP to create panned sound effects. The Pan plug-in was used to convert the device's end-effector position into appropriate pan values. As a result, if the participant hit the sphere on the right hand side, he/she would hear the sound coming from the left hand side (in experiment 1).

C. Procedure

The study was subject to Middlesex University's ethical regulations and an information package was provided to each participant before being admitted to the study. Subjects were individually briefed at the beginning of the experiment following informed signed consent. Before interacting with the system, each participant was informed that he/she would be exploring an interactive painting using a haptic device for as long as they wanted to. For experiment 1, subjects were instructed that they would explore the interactive painting twice and that the experiment would end once they completed a questionnaire. For experiment 2, subjects were instructed to either interact with the painting on their own and with another participant. Following the instructions, subjects were left alone to explore the painting and asked, once finished, to bring the completed questionnaire to the experimenter.

D. Outcome Measures and Data Collection

We collected both qualitative and quantitative data. Participants were assessed through a 8-item (experiment 1) and a 7-item (experiment 2) questionnaire using the methodology suggested by O'Brian and Toms [16] which evaluated some specific aspects of user experience and engagement. The questionnaires resulted in a 3-item factor for Endurability (the likelihood of remembering an experience and willingness to repeat it), a 2-iem factor for Usability (the ease of use and learnability of a human-made object) and a 3-item factor for Focused Attention (attention to the exclusion of other things). The participants' responses were collected based on a 7-point Likert-type scale, which required participants to rate their level of sat-dissatisfaction. In the second part of the questionnaire, four questions based on checklist items and open/closed structures were used to collect participants' opinion and previous experience.

In addition audio-visual data (from user's interaction with the painting) was collected using three camcorders, while kinematic data (positions, velocities) recorded using the robot (Novint Falcon).

IV. RESULTS

A. Experiment 1 (ball painting)

Fig. 4 illustrates both the central tendency and variability of the three scale factors (mean scores) when compared with Phase A (haptics only) and Phase B (haptics + sound).

The mean scores assessing the Endurability factor (1) and Focused Attention (2) indicate no significant differences between the two groups, while group 2 seem to rate higher the Usability factor (3), i.e. subjects seem to find exploring the painting with touch + sound easier than just with touch. Paired t-tests confirm that statistically no significant change occurs in scale-factor (1, 2) (p=1, p=0.93) and although scale-factor (3) show higher rate for group two rate (4.4 for group 2 and 3.5 for group 1) the p value was 0.076. Thus suggesting that the order of the phases did not have a major impact on subjects' experience and engagement with the interactive painting.

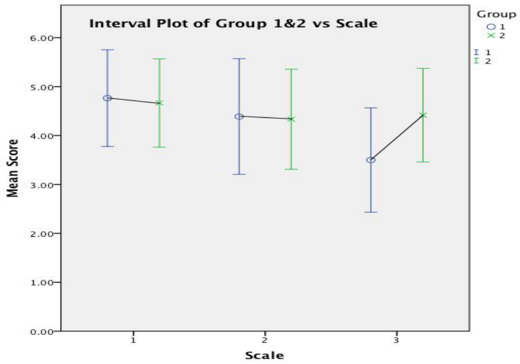

Fig. 4 Comparison of the mean scores for each of the three scale factors measured between group 1 and 2 for Experiment 1.

In order to assess the value of the interaction, the total time spent on each of the phases per group as recorded by the system was plotted (Fig. 5). Because the groups are not homogeneous in that no attempt is made to match them, only the relative data is useful for analysis. Fig. 5 shows no significant difference between phases for group 1 but a longer time for Phase B (touch + sound) with group 2, which could be associated to the phase order (i.e. group 2 experienced touch + sound first). The questionnaire results show that participants were on average willing to spend more time (99.32 sec) exploring the painting during phase B. The questionnaire results indicate that participants were actually willing to spend more time at the task than actually spent (as recorded by the system and shown in Fig. 5).

To assess the effects of the interaction on participants' movements, a further analysis was made comparing the number of times subjects touched the 'ball' (Fig. 6) and comparing the mean movement velocities (Fig. 7) for each group and phase. Fig. 6 indicates that the mean of total hits (i.e. number of times subjects touched ball) is higher during phase B (touch + sound) for both groups. Interestingly, while group 1 show significantly higher velocities during phase B (Fig. 7), group 2 shows higher velocities during phase A, albeit of equivalent velocity magnitude as observed in group 1 during phase B.

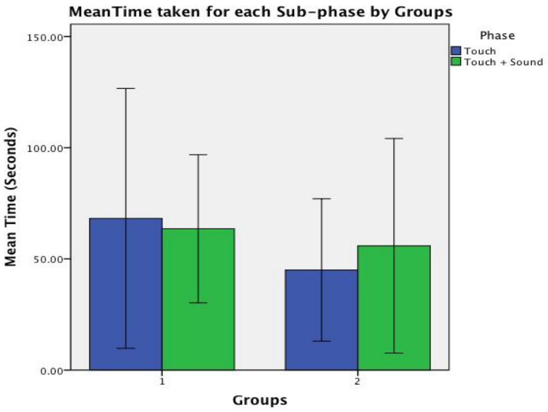

Fig. 5 Chart of the mean total time spent exploring the ball painting in experiment 1 for each phase in both groups.

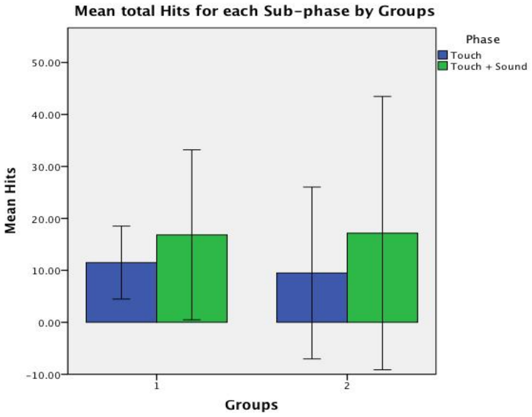

Fig. 6 Chart of mean total hits for each phase in both groups.

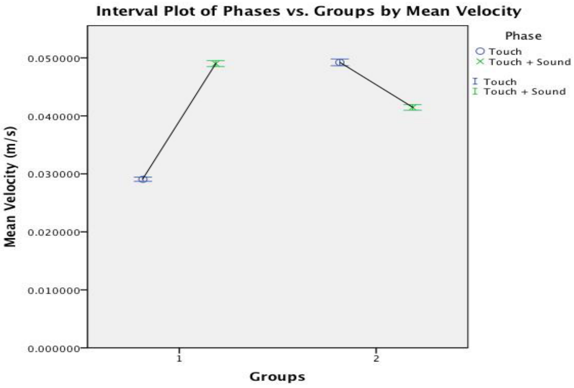

Fig. 7 Comparison of the mean velocities during experiment 1 for each group by phase

A. Experiment 2 (water painting)

Similarly to experiment 1, Fig. 8 illustrates both the central tendency and variability of the three scale factors when compared with the two groups (singles and pairs).

The results are identical to those obtained with experiment 1, with main difference being the mean scores assessing Focused Attention (2) indicating in contrast higher scores during paired user interaction (group 2). However, paired t-tests confirm that statistically no significant change occurs in all three scale-factors (p=1, p=0.158, and p=0.185). The questionnaire responses revealed that participants were willing to spend more time exploring the water painting in a group (alone 255.6 sec, in a group 436.8 sec). In contrast, the total time recorded by the system show higher times spent exploring the painting than what participants were willing to spend, but no significant differences were found in between groups as recorded by the system (alone 455 sec, in a group 451 sec). However, while assessing the effects of the interaction on participants' movements by comparing the number of times subjects touched the 'water' (Fig. 9) and comparing the mean movement velocities (Fig. 10) for each group, it is apparent that subjects performed more movements while interacting in pairs.

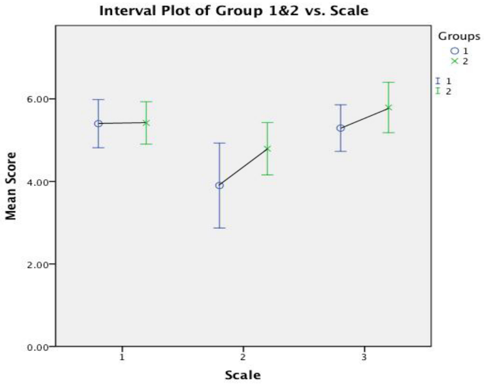

Fig. 8 Comparison of the mean scores for each of the three scale factors measured between group 1 and 2 for Experiment 2.

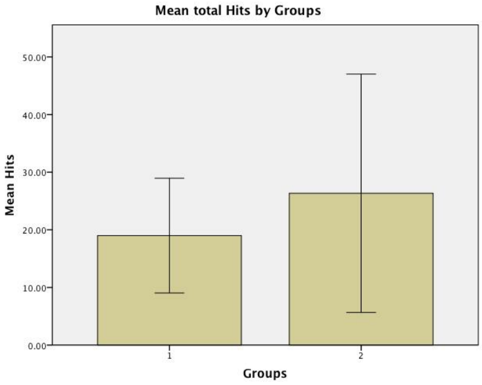

Fig. 9 Chart of the mean total hits. Number of times subjects touched the water in experiment 2.

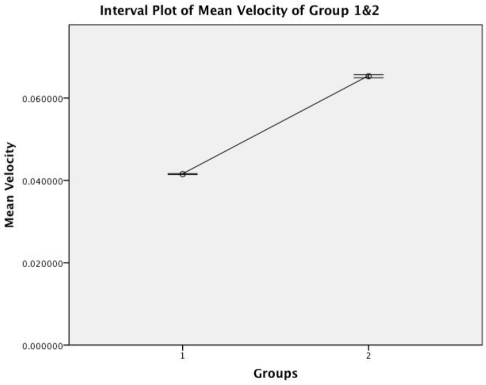

Fig. 10 Comparison of the mean velocities during experiment 2 by each group.

V. DISCUSSION

What appears to come out from the results is that there are no major differences in terms of engagement – all subjects were happy to participate and seem to have enjoyed the experience.

It emerges that haptic with sonic interaction was preferred over just haptic interaction. The kinematic data results presented on the previous section together with observation analysis on the audio-visual recordings reveal some potential benefits to our approach.

While subjects interacted in pairs, velocities were higher thus implying more movements were made, however further video analysis revealed not only interesting ways participants communicate, but also specific patterns started to emerge suggesting in some cases that the technology completely surpasses the work of art (painting) as subjects focus their attention on the device rather than the painting. Although it was apparent that some subjects moved their attention away from the painting and started exploring it using their imagination via haptic and sonic interactions, one possible explanation for some of the increased attention on the device, is perhaps in part due to the fact that participants could see the device exposed through the top of the plinth. To keep the attention focused on the painting for future experiments, it would be advisable to make the haptic device as unobtrusive as possible.

It appears that this form of interaction might help developing analytical skills. The best experiment 2 performing subject, while interacting with the water painting on his own, was searching for more detail in the painting and explored carefully. This behavior was consistent with the other subjects. Where we can observe some subjects looking cautiously at the painting and trying to match the visual detail with the haptic and sonic cues. The subjects challenge the limitations and boundaries of the haptic-sonic cues in relation to the static visual (painting).

Imagination development seems to be linked to some emotional attachment. One participant expressed in great detail her emotional attachment to the sounds and painting, referring to a childhood experience. The more she became engrossed in her own world, the more she stopped looking at the painting and was interacting with the haptic device and the sounds. We also observed that when the subjects finished with the analytical part and therefore detach their attention from the painting, their next exploration stage focused on the haptic-sonic cues. It appeared that subjects used more imagination, i.e. creating their own visual/virtual environment. Interestingly, we found that subjects moved between varying degrees back and forth analytical and imagination exploration.

The interactive painting appears to promote spatial skills realisation. When subjects were presented with the 2D image (static painting), they explored the painting using haptic-sonic cues as a 3D space. We could observe subjects mapping the 2D reference with the haptic device, by exploring the boundaries first. Doing so, subjects seem to create a 3D environment in their mind matching the virtual haptic environment by mapping the left and right borders of the painting with the left and right boundaries of the haptic workspace. Subjects first map the virtual height and depth of the painting with the physical boundaries of the haptic workspace and then explore the space between these boundaries. We noticed different levels of aptitude to this skill. Some explore freely, some for example get stuck at the bottom of the painting/under the ball (experiment 1).

One solid observation from this pilot study, is that sound clearly enhances the haptic experience. When subjects felt, for example, their hand going into the water (experiment 2), they experienced haptic feedback with direct correlation to the sound (splashing). The sound is also directional, for example, move hand to the left, splash sound to the left. The subject notices as the hand movements get faster, the haptic cues increasing, and so does the intensity of the splash sound. This relates to several different elements of the paintings.

Subjects increase activity when the haptic and sonic cues match the virtual 3D environment with the 2D painting.

With the painting in experiment 1 (ball painting), participants were more cautious than those in experiment 2, but perhaps this is due to experiment 1 promoting shape determination and experiment 2 a more explorative behavior. Group interactions were engaging and participants made more movements, which were in nature ballistic (experiment 2). Participants seemed to enjoy the collaborative exploration, engaged in communication, and shared and negotiated exploration strategies.

VI. CONCLUSION

This paper presented a new approach exploring the concept of art exploration with group interaction through an interactive painting. Our approach in contrast with typical haptic interaction does not use dynamic visual cues mapping the haptic world. In our case, we use a static painting, which prompts for some imagination to occur aided by immersive haptic and sonic cues carefully designed to enhance the main elements in the paintings used for the study.

Our goal is to explore the social nature of art exploration and education to promote creative expression and playful activity beyond the clinic or home. The results from this initial pilot study are encouraging. Participants seemed engaged and it appears that the interactive painting paradigm encourages development of analytical skills, imagination, promote spatial skills realisation and enhance touch/hearing sensory channels.

While the results obtained with this pilot study only allow for speculating on the value of the interaction for rehabilitation of cognitive and motor deficits, our approach might be beneficial to children with cognitive, learning and sensory impairment and people recovery from a stroke. Research into the relation between music and cognition and music and communication has highlighted the importance of rhythmic beat and synchrony for learning, motor control, social skills, and emotional well-being. Recent work in music science has shown that synchronizing in time (entrainment) with others is a fundamental part of human communication, enables empathy and sense-making, and affects/improves memory [16]. Some qualitative evidence has been found to support the existence of intrinsic benefits of participation in creative arts to people with a range of disabilities including Cerebral Palsy, mild to severe intellectual impairment, Down Syndrome and Autism [16].

Perhaps simple explorations of carefully designed interactive artifacts available in public spaces could have a positive impact on rehabilitation. Future developments could look at such ideas to engage patients in activities that might not seem a priori as 'rehabilitation' but promote self-expression, cognitive development, social connectedness and result in the practice of a range of movements (e.g. tapping into relation needs and limb non-use issues observed in chronic stroke patients). Our ongoing work aims to initially explore such concepts with stroke patients, in particular to evaluate how the quality of movements change when interacting with haptic paintings and how this affects motivation.

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