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Utilizing Media Arts Principles for Developing Effective Interactive Neurorehabilitation Systems

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Abstract—**This paper discusses how interactive neurorehabilitation systems can increase their effectiveness through systematic integration of media arts principles and practice. Media arts expertise can foster the development of complex yet intuitive extrinsic feedback displays that match the inherent complexity and intuitive nature of motor learning. Abstract, arts-based feedback displays can be powerful metaphors that provide re-contextualization, engagement and appropriate reward mechanisms for mature adults. Such virtual feedback displays must be seamlessly integrated with physical components to produce mixed reality training environments that promote active, generalizable learning. The proposed approaches are illustrated through examples from mixed reality rehabilitation systems developed by our team.**

I. Introduction

THERE is a profound growth of movement rehabilitation research applications using novel interactive systems. Such systems employ various combinations of embodied controllers (e.g. Kinect), light robotic interfaces (e.g. Manus) and portable/wearable monitoring equipment (e.g. iphones) to track a patient's movement. Automated analysis of the movement data drives digital feedback: computer graphics and digital sound environments of various immersion levels. Such interactive systems allow patients to self-assess and improve their movement. The growing interest in semi-automated Interactive Neurorehabilitation (INR) is being driven by the fast evolution and lower cost of these technologies, the need to encourage active learning by the patient, and by the continuous decrease in available support for extended traditional neurorehabilitation.

Many INR applications are still being referred to as "virtual reality" therapy even though the breadth and variance of INR spreads well beyond the strict definition of "virtual reality". Within the interactive media field, virtual reality refers primarily to environments that immerse the participant within a completely simulated space where as mixed reality environments integrate both digital and physical elements and aim for various degrees of immersion. The amount of virtual elements and virtual immersion of each environment determines the placement of that environment on a "virtuality" continuum (bounded by virtual and physical end points) [1]. While terminology is still being worked out, the key goals for the use of INR in movement therapy are being established: a) provide long term recording and quantitative understanding of movement that is correlated to clinical outcome measures, b) augment intrinsic feedback with extrinsic feedback streams so as to promote reacquisition of motor skills, c) facilitate the active engagement of patients in extensive daily training, provide motivation and counteract boredom and fatigue [2,3,4].

There have been many promising results reported for the use of INR in movement therapy [2]. However, many of the studies use different methodologies and have a small number of participants. We still lack consistent, large-scale experimental evidence that establishes clearly the added benefits of INR and best approaches to achieving the three overarching goals outlined above. Some more recent studies are beginning to address this need and setting a trend for extensive INR studies [5]. The pace of the INR experimental evidence will continue to accelerate but it will not be able to keep up with the pace of advancements in interactive media and the growing need for self-supervised therapy at the clinic and the home. It is therefore important for the field of rehabilitation to also leverage strong evidence from other fields to help establish best practices in INR. This paper discusses how well established principles from media arts, media computing and the cognitive sciences can assist INR systems in achieving their three main goals. Approaches taken by our team to achieving the first goal (recording and quantitative evaluation of functional movement) is presented in detail elsewhere [6]. This paper will focus on principles for achieving the second and third goals of INR systems (augment intrinsic feedback and facilitate active engagement).

II. Media Arts Principles for Structuring Augmenting Feedback

Traditional biofeedback approaches to producing extrinsic feedback that augments intrinsic feedback during movement rehabilitation focus on simplicity. Extrinsic feedback displays one element of the movement either in terms of results (was the goal of the action achieved – i.e. was a target reached accurately in an reach and grasp movement) or in terms of performance (display of a movement parameter during the performance – i.e. elbow opening during a reach and grasp movement)[7].[1] In early biofeedback applications a driving reason for such simplicity in extrinsic feedback was technological limitations (it was

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[1] For the purposes of this paper we will define intrinsic feedback as information produced directly by the movement and extracted by the patient through their own sensory mechanisms without assistance and extrinsic feedback as information on the movement provided by external agents.

hard to capture and display accurately many elements of the movement in real time). However, even as technological limitations dissipated, the focus on single, simple streams of augmenting feedback in INR persisted due to concerns of cognitive overload for the patients. Each complete limb movement produces multiple intrinsic streams of information and the addition of multiple extrinsic streams could overload the patient. The overloading concern is based on models of cognition that treat human beings as computing machines that process the world mentally [8]. Phenomenology [9], ecological psychology [10], embodied learning [9] and cultural cognition [8] theories and research have challenged the Descartian model of learning exclusively through mental processing. Embodied cognition theories support that learning results from the statistical integration of multiple streams of information provided by all our senses while we physically interact with the world. Recent approaches to motor learning also engage the concept of redundancy where multiple, integrated circuits inform and control an action and guarantee robustness [11]. Gibson's ecological psychology model (and many of the embodied cognition theories that followed) is grounded on the assertion that humans aim to understand the underlying rules and dynamics of their actions and of the environments in which they function rather than mentally processing the appearance of the environment. Along the same lines current rehabilitation practices put emphasis on the acquisition of the basic motor elements (such as muscle or movement synergies) that underlie functional task accomplishment [4]. Treating the action as a whole and revealing relations between goal acquisition (i.e. grasping an object), activity level parameters (i.e. end point speed) and body function parameters (i.e. elbow extension) is necessary for relearning elemental motor patterns [4,11].

Embodied cognition theories propose that INR systems focused on simple extrinsic feedback have limited ecological validity for, and limited impact in, complex learning contexts. Systems that only reveal results of an action (like the Wii tennis game) without revealing any of the movement dynamics leading to these results do not assist the learning of elemental, generalizable motor patterns. Systems that track movement performance elements but only display one element at a time (i.e. elbow opening during reach and grasp) do not reveal interrelationships between multiple movement components (i.e. elbow opening and torso compensation) that can help patients improve their actions and functionality. Systems that display simple representations of the action and task being trained (i.e. showing a virtual representation of the arm of the patient reaching and grasping during reach and grasp training) cannot focus on subsets of motor elements or reveal specific, complex dynamics. Elements of "life-like" representations cannot be removed or exaggerated without disrupting the representation and possibly confusing impaired subjects who rely on the system for movement control. Thus, representational systems are hard to adapt to address needs of different patients at different stages in the training. Representational systems also have to simplify the action space as virtual representation of the full complexity of physical reality is impossible. This "close to reality but not reality" relation causes interaction artifacts [12] that may diminish the usability of the system for impaired subjects. Overall, INR systems that use simple displays can only be useful in early stages of training when singular aspects of the movement are being trained [7, 3]. Once training advances to more holistic stages, where multiple components of elemental motor patterns and of functional tasks are addressed in parallel, simple displays lose their effectiveness. The user quickly realizes the complexity gap between the actual movement and the simplistic representation and abandons the metaphor of the display as a useful learning mechanism.

INR systems should utilize multimodal extrinsic feedback displays that can potentially reveal the state and dynamics of each key movement component of a task being trained as well as the interrelationships of components. These displays should be adaptable and able to focus on the subset of parameters important to each patient at each stage of their therapy. Effective INR displays need to provide all this rich information in an intuitive manner so that the patient can extract the necessary information with minimal guidance and without being overwhelmed or distracted from their training goals. Theoretical and compositional principles from the arts, as applied to the creation of art-works, can form the foundation for the construction of rich, intuitive displays for INR. Contrary to some traditional biofeedback approaches that consider rich and intuitive displays to be incompatible, the arts, for centuries, have been developing principles for the creation of powerful, rich experiences that can be intuitively perceived and appreciated by a great number of people. As audience members gradually increase their familiarity with an artwork they uncover some of the deeper structures. This gradual revealing of complexity in an experiential interaction maintains the interest of the user and increases her engagement in and understanding of the experience. For example, the experience communicated by Pissarro in a painting of Montmartre (Fig. 1) can be immediately appreciated by all audiences regardless of training. Increased interaction with the painting reveals that

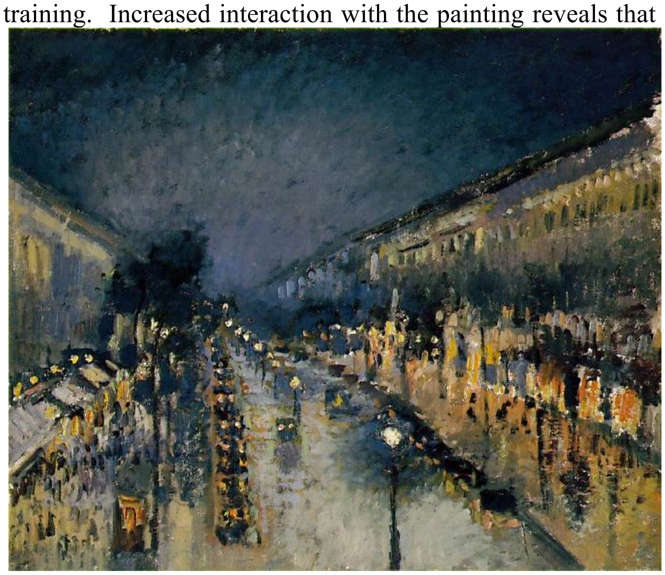

Figure 1. Boulevard Montmartre at Night, by Camille Pissarro, 1897, London National Gallery; an example of a complex and intuitive display

the experience is structured through subtle relationships of dots of paint.

Foundational principles from the arts can help INR system designers achieve the following:

- select optimal display modes for each movement component (i.e. choose to display spatial information through visual means and timing information through auditory/musical structures)
- compose effective, intuitive displays (i.e. communicate depth accurately through rules of visual perspective, timing characteristics through specific rhythmic patterns, specific emotion through lighting effects and harmonic choices in audio)
- synthesize multiple display streams into one coherent experience (i.e. combine auditory displays of two movement components into one polyphonic music composition; combine spatial information in visuals with timing information in audio to create an integrated display of velocity; combine explicit information of successful goal completion in visuals with implicit rewards through sound)
- develop effective feedback fading structures both in terms of on/off patterns and in terms of summaries. For example, once a musical rhythm or tonal key has been established in the user's mind it can be discontinued from a display with short future repetitions reestablishing it as needed [13]. Film composition techniques allow for the creation of higher-level summaries that successfully reference the more detail information provided at lower levels (i.e. in Kieslowski's Red, Blue, White trilogy short image and sound motives reference extensive sections and ideas developed across the three movies).
- structure interactive experiences that maintain coherence across extensive time spans. For example, intuitive memory of tonal space in music, which allows a listener to tie together a long symphonic work [13], can also help the user integrate auditory feedback received over an hour of therapy.

The application of arts principles to generation of extrinsic feedback for INR is most effective when abstract displays are used (instrumental music compositions, animated abstract shapes, multimodal fictional storytelling etc). In such abstract contexts optimal display components can be constructed and manipulated freely across many dimensions without concerns for strictly representing the reality of the task being trained [14,15,20]. Attention of the user is shifted to structural elements of the display, and to the corresponding movement elements (i.e. how does trajectory and speed of end-effector relate), rather than the details of the resulting manifestation (i.e. does the representation of the hand look accurate in the display). Abstract displays are not tied to specific representations and therefore can be used across many different tasks. Since abstract interactions in movement rehabilitation focus the user on discovering the elemental motor patterns that underlie successful task accomplishment, learning that occurred during one task (i.e. bell-like velocity profile during reach and grasp) can also transfer to training of other related tasks (reaching and pushing a button) when using the same abstract display. This process facilitates generalazible motor learning [16]. The feedback sensitivity/bandwidth can also be easily adjusted when using abstract displays. Abstract elements can change their behavior and sensitivity without producing a sense of conflicting rules for the user. Sensitivity changes are much harder to achieve in representational environments (it is hard to convince a user that a representational environment can change its structural rules).

III. FACILITATING ACTIVE LEARNING THROUGH ARTS-BASED MIXED REALITY

One of the main benefits of arts based abstract displays is the ability of such displays for re-contextualization of training tasks. The arts throughout the centuries have aimed to help people gain new perspectives so they can better address the complexities of everyday life [17,18]. Overall, metaphors (artistic and otherwise) are a powerful learning mechanism helping people to overcome emotional, physiological and intellectual hurdles [19]. Mapping performance of training tasks to interactions with abstract artworks helps patients gain some distance from possible frustrations they face when attempting to perform these functional tasks in daily life. From this more detached perspective patients can focus on relearning the elemental motor patterns communicated by the abstract displays. As the patient begins to relearn motor skills, the abstract displays can be faded and the focus can be shifted to functional training task in physical space (i.e. grasping and transferring physical objects).

Smooth transitions from metaphoric space to actual functional space require the use of mixed reality systems; systems that integrate seamlessly virtual displays with physical objects [14,15]. In such systems the amount of re-contextualization necessary at each stage of the therapy for each patient can be fully controlled. Exercises can be performed in virtual space (with no physical objects present), in mixed reality spaces with various increments of "physicality" (achieved by increasing the amount of physical objects engaged in the exercise and reducing the amount of virtual information) and in purely physical space (with no virtual information). Such systems require careful design to guarantee that the addition of physical objects and the passing into mixed reality feels like a natural continuation of the virtual experience. The integrated design of the virtual displays, the physical objects and the transition protocols are crucial to this continuum. Mixed reality systems help the transference of learning achieved in virtual environments to physical, functional reality thus addressing a key concern with virtual training systems [2].

Arts-based, abstract mixed reality environments provide intrinsic reward value, a crucial element for sustained training of populations of mature adults. While performing exercises adults are able to create music and graphics compositions and develop stories. Such cultural interactions with creative content and emotional and intellectual reward value are much more appropriate and engaging for adults than games in which realization of exercises produces extrinsic rewards in the form of collection of points. The large-scale formal principles of arts compositions are highly fitted to addressing the structural needs of long-term rehabilitation. A well-written book or television series can keep the attention of its reader or audience over months or even years. Reading a book takes place over many days but feels continuous; within minutes of re-starting to read, the full experience achieved through earlier readings returns.

The assessment of the emotional, attentional and learning effects of an arts experience that is passively consumed by a user (i.e. listening to music) has been primarily tackled through qualitative means (i.e. narrative review) and tracking of long-term trends (i.e. popularity) [18]. However, in interactive systems, where the effect of the experience is associated with a change of behavior that can be measured (i.e. change in kinematics of a reach and grasp movement), detailed, real time, quantitative evaluation is possible and can drive effective adaptation of the experience [14].

IV. EXAMPLE SYSTEMS, APPLICATIONS AND FUTURE WORK

Subsets of the arts-based approaches to INR mentioned in this paper are already in use worldwide and producing promising results (see references in [20]). Our team at the School of Arts, Media and Engineering (AME) at ASU, has developed an Adaptive Mixed Reality Rehabilitation system (AMRR) for upper extremity training of stroke survivors (fig. 2) that integrates all principles discussed [14,15]. The system uses abstract multimodal displays based on arts principles and integrates these displays with physical objects. The system can provide digital feedback on any combination of 34 key kinematic parameters of reaching tasks. These parameters are extracted through marker based motion capture and pressure sensors. The system is highly adaptive. The therapist can adapt the type and sequence of training tasks, the dose of each exercise, the number and combination of kinematics parameters being displayed by the digital feedback and the sensitivity of each mapping. Results from prior pilot studies and preliminary results from a current clinical study show that the system is accepted by the stoke survivors and therapists, is highly intuitive and promotes active learning by stroke survivors with differing levels and types of movement impairment [14,20].

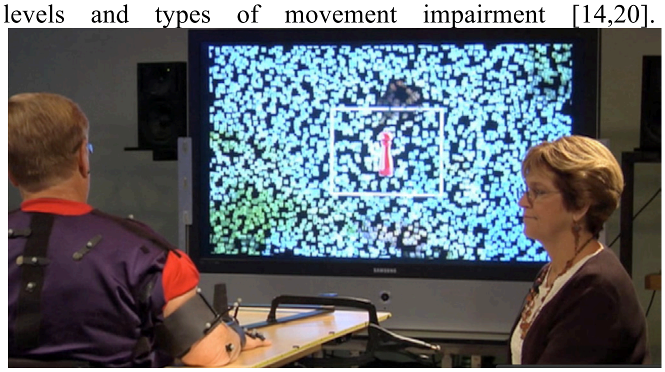

Figure 2. Interacting with an abstract, arts-based display during stroke rehabilitation (AME AMRR system).

Through the development of our system, we have identified a set of high-level design guidelines for the construction of interactive feedback for assisting motor learning [20] and have developed an innovative computational framework to support interactive movement rehabilitation. The computational framework currently has two key components: i) a computational index to measure learning in terms of kinematic performance [6] and, ii) algorithms to extract correlations between variables of kinematic performance and feedback [21]. Through further development of this framework we will be able to measure feedback effectiveness and active learning at multiple time scales [20]. We are also extending the framework by monitoring brain activity patterns through EEG during the interactive learning process in anticipation of adding this as a third class of variables [22]. We are in the final stage of developing a low cost version of our system for extended (> 1 year) home-based rehabilitation of stroke survivors [23]. The system will test adaptive usage of three levels of summary feedback with each higher level retaining pertinent information from lower levels. Principles from media arts are used to construct and unify all levels of feedback.

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