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Novel Design of Interactive Multimodal Biofeedback System for Neurorehabilitation

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Abstract—***A previous design of a biofeedback system for Neurorehabilitation in an interactive multimodal environment has demonstrated the potential of engaging stroke patients in task-oriented neuromotor rehabilitation. This report explores the new concept and alternative designs of multimedia based biofeedback systems. In this system, the new interactive multimodal environment was constructed with abstract presentation of movement parameters. Scenery images or pictures and their clarity and orientation are used to reflect the arm movement and relative position to the target instead of the animated arm. The multiple biofeedback parameters were classified into different hierarchical levels w.r.t. importance of each movement parameter to performance. A new quantified measurement for these parameters were developed to assess the patient's performance both real-time and offline. These parameters were represented by combined visual and auditory presentations with various distinct music instruments. Overall, the objective of newly designed system is to explore what information and how to feedback information in interactive virtual environment could enhance the sensorimotor integration that may facilitate the efficient design and application of virtual environment based therapeutic intervention.***

Keywords— **virtual reality, biofeedback, neurorehabilitation.**

I. INTRODUCTION

DEVLOPMENT of new technologies propels the application of various novel methods in neurorehabilitation. Virtual reality (VR), one of new technologies, has been applied extensively in both psychological [1] and physical [2] rehabilitation in recent years. The advantage of using VR based system in neurorehabilitation are that (1) the motor or cognitive deficits can be quantified through objective evaluation, (2) the presented virtual environment and training program can be easily controlled and adjusted, (3) the environment simulates the real-life scenario to provide purposeful but augmented environment that might enhance the training effectiveness, and (4) VR motivates patient to actively involve in task training. Studies concluded that VR showed potential in assessing the impairments, disabilities, and handicaps [3, 4], and in facilitating motor functions and cognitive ability in brain damaged people [5, 6].

Our previous study has designed an interactive multimodal environment (IME) based biofeedback system for repetitive reaching and grasping training [7]. Patient tried to reach a virtual teapot within a virtual living room scene displayed on a large 2D screen (Fig. 1). The task and environment are straightforward and mimic the physical reaching task. The endpoint trajectory was selected as biofeedback parameter. The visual and auditory feedbacks were assigned so as to take full advantage of the affordance of each sense. Visually, feedback cue constrains the spatial accuracy of the endpoint. More innovative feature of this system was the way we designed auditory feedback through music composition that interacts with a subject's spatiotemporal accuracy of endpoint trajectory. Five hemiparesis patients were tested. The result indicates that patients could perceive and control assigned biofeedback parameters. The visual augmented feedback improved the spatial consistency of the endpoint position during reaching. The auditory augmented feedback contributed improvement of the smoothness of endpoint trajectory, and the spatiotemporal consistency of reaching performance. After 3-5 training sessions, patients indicated faster, smoother, and more applied joint range of motion while reaching [4].

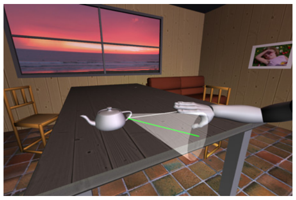

Fig. 1. Previously design interactive virtual environment.

However, the problems were exposed from previous study. First of all, the design should increase the number of parameters mapped beyond just the endpoint trajectory. This is because the feedback of endpoint usually cannot elicit patient's attention to localize the problematic motor deficit. For example, if the endpoint path was out of error boundary that was fed back through visual cue, the response of the patients was to recruit compensatory movement from trunk to correct the error rather than to coordinate the movement of joints, which may develop into inappropriate reaching pattern. Secondly, all VR based physical therapies are facing the same question: why training in the VR? We hypothesize that the advantage of VR is not only able to deliver real-life experience such as the design in Fig. 1, but more importantly to enhance sensorimotor integration through novel augmented multimodal feedbacks that are different from the familiar perceived stimulation in real life. Such fresh stimulation might further enhance plasticity. If our hypothesis is true, the VR could be designed into environment with fantasy and abstract cues. Thirdly, although patients reported preference on previous designed

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IME environment, the engagement reduced when patients adapted to the straightforward feedback environment such as shown in Fig. 1. To keep patients' interests, more enriched feedback environment and more challenging training programs should be included. Additionally, our previous design simplified the IME feedback stimulation to avoid information overloading the perception of neurally injured patient. Although abstract environment requires more information processing capability, such an environment could help patients to train perception or cognitive functions such as converting imageries into spatial information of the movement and enhance sensorimotor integration.

This paper mainly focused on the new design of IME based biofeedback system with abstract and enriched presentation.

II. METHOD

A. System Overview

The biofeedback system integrates five computational subsystems: (a) motion capture, (b) motion analysis, (c) audio feedback, (d) visual feedback, and (5) database for archival and annotation (Fig. 2). All five subsystems are synchronized with respect to a universal time clock. Six-camera based motion-capture system tracked 3D position of reflective markers with 100Hz sample rate. The real-time motion analysis subsystem smoothes the raw sensing data, and derives an expanded set of task specific quantitative features. This engine sends the analyzed data to audio, visual, and archival subsystems at the same frame rate. The audio and visual subsystems adapt their auditory and visual response dynamically to selected motion features under different feedback environments. The archival subsystem continuously stores the motion analysis as well as the feedback data with universal time stamp, for the purpose of annotation and off-line analysis. Our system situates participants in an IME, where physical actions of the arm are closely coupled with media feedback.

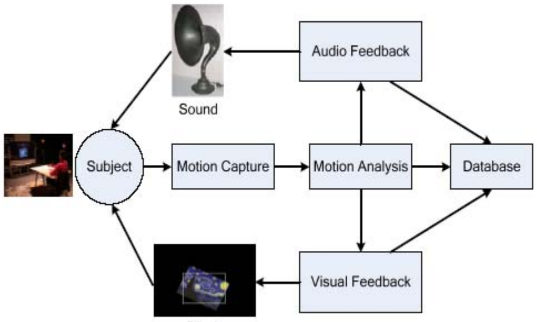

Fig. 2. System diagram.

B. Hierarchical Level of Movement Features

Multiple movement features were extracted and constructed into hierarchical levels (Table 1). The levels are defined based on the domain knowledge from therapists and the mechanism of motor control.

From level 1 to level 6, the parameter shifts from general movement feature to more detailed movement components. The biofeedback parameters are mapped starting from lower level that is considered as more important feature for trained task. Because the endpoint trajectory was reported as the control variable for goal-directed reaching task [8], the endpoint trajectory and hand-to-target relationship were inserted into level 1. Level 2 includes the joints determining the arm opening. Level 3 contains the joints affecting the reaching direction. The parameters in level 4 can be used to monitor the compensatory movement from trunk. The features in level 5 and 6 define the grasping performance.

TABLE I
HIERARCHICAL MOTION FEATURES

Level	Features
1	3D hand trajectory/relative error to the predefined path
2	Shoulder flexion/elbow extension
3	Shoulder rotation/shoulder abduction
4	Trunk flexion/trunk rotation/trunk lean/shoulder trajectory
5	Supination/Pronation
6	Wrist extension

C. Multi-Goal Framework

Reaching and grasping task includes three sub-goals in the action space reaching and preparing to grasp the target, opening of the arm joints, and the flow of the movement. All sub-goals are computable from motion features.

(1) *Reaching and Grasping*: The goal of the task is to reach out for the target with minimum spatial error, correct hand orientation, and speed.

(2) *Opening*: In addition to goal (1), subject should open the arm. Neurological injured patients might not achieve this sub-goal by means of torso movement compensation.

(3) *Flow*: This goal characterizes the coordination in the upper-extremity while reaching and grasping.

D. Coupling Action to Feedback

The structure of the feedback environment and its relationship to the achievement of the goals were based on well-established principles regarding the role and function of art [9]. To achieve initial engagement the environment must be aesthetically attractive, easy to use and intuitive. Having attracted the attention of the patient the environment must maintain their attention through evolution of form and content. At the highest level of its structure the environment must communicate to the patient the messages that can encourage the accomplishment of the movement goals. These messages are: *reach*, *open*, and *flow*. The mappings and content follow a similar structural hierarchy as the movement parameters and goals with sub-message levels supporting the communication of each larger message. As is the case of movement parameters, there are feedback parameters that the subject can quickly understand and control, parameters that require practice to control and subconscious parameters supporting the achievement of the consciously controlled goals.

E. Abstract Biofeedback Environment Design

In the abstract environment, subject faces more challenging feedback to motor mapping. Visually, the subject is presented with a picture in a frame. The picture explodes into thousands of particles, and then the subject is able to reassemble the picture by completing the reaching and grasping movement. The vertices locate the particle in 3D space, while the texture coordinates provide a 2D mapping to a color from the image. The motion of the particles has five components: rotation angle that maps the hand orientation, and four motion vectors: explosion, turbulence, horizontal pull, and vertical pull that feed back the spatial accuracy of endpoint.

The accompany music is composed by the dynamic movement of upper-extremity. The detailed design and mapping were list in table II, III and IV. For example, the shoulder extension and elbow extension introduces an accompaniment played by string instruments and the opening of the shoulder introduces an accompaniment played by winds (Table IV). This synchrony of chords, like joint synchrony, can only be controlled subconsciously especially by musically naïve subjects. When synchrony is achieved and the chords are in harmony the subjects knows it. However, when that is not the case conscious analysis in real time will offer little to the subject. Synchrony and the resulting harmony need to be achieved through experimentation.

F. Validation Metrics

The following mathematical equations were applied to quantify the goal achievement and task performance of patients.

(1) Spatial Error

Two spatial errors were considered: (a) distance between hand and target and (b) hand orientation. The normalized hand-target distance is represented as $d_1 = \frac{\|X_h(t_3) - X_T\|_2}{\|X_h(0) - X_T\|_2}$. where X_h is 3D position of hand marker, X_T is the target position, t3 is decelerating ending time and $\| \|_2$ is L2 distance metric. The error in hand orientation d_2 is defined as the distance between actual joint angle and desired position.

The overall spatial accuracy of a target reaching trial is the weighted linear combination of hand-target distance and hand orientation accuracy: $s = w_1^s d_1 + w_2^s d_2$ (1). Wherein, w_1^s and w_2^s are weights.

2). Arm Openness

Shoulder extension and elbow extension were applied to quantify the arm openness. In the similar manner with spatial error, the shoulder openness and the elbow openness are defined as the relative error with respect to the desired shoulder extension and elbow extension:

$$p_s = \frac{|\theta_s(t_3) - \theta_s^T|}{|\theta_s(0) - \theta_s^T|}, p_e = \frac{|\theta_e(t_3) - \theta_e^T|}{|\theta_e(0) - \theta_e^T|} \qquad (2).$$

where p_s and p_e are the error in shoulder openness and elbow openness respectively, θ_s and θ_e are shoulder and elbow extension angle, and θ_s^T and θ_e^T are the desired shoulder extension and elbow extension respectively. Both p_s and p_e are numbers between 0 and 1, zero means full openness and ones mean no openness. The overall arm openness is defined as the linear combination of shoulder openness and elbow openness: $p = w_1^p \cdot p_s + w_2^p \cdot p_e$, where w_1^p and w_2^p are weights.

TABLE II
MUSICAL FEEDBACK OF ENDPOINT TRAJECTORY

Movement State	% of Reaching Distance	Musical Feedback Harmony
	0.00-0.19	I^{ma7}
Reaching	0.19-0.50	vi
	0.50-0.85	V^7/IV
Grasping	N/A	IV
	0.63-1.00	ii^7
Returning	0.29-0.63	V^7
	0.00-0.29	I

TABLE III
MUSICAL FEEDBACK OF VELOCITY OF ENDPOINT TRAJECTORY

Velocity Range	Pulse Subdivision
0.00-0.192	2
0.192-0.410	3
0.410-0.640	4
0.640-0.780	6
0.780-1.00	8

TABLE IV
MUSICAL FEEDBACK OF SHOULDER FLEXION/EXTENSION

Instrument	Reaching		Returning	
	Mv	*t*d	Mv	*t*d
Flute	0-60	100-300	0-60	100-300
Clarinet	50-60	200-600	50-60	200-600
Bassoon	0-60	200-600	0-60	200-600

Note: Mv: Musical Instrument Digital Interface (MIDI) velocity, *t*d: MIDI duration. The elbow extension is mapped in the similar manner.

3). Flow Error

Intuitively, the flow error is related with the smoothness of speed curve. The smoother the speed curve, the less the flow error is. Two measurements of curve smoothness -(a) zero cross number and (b) polynomial curve fitting error were introduced. Then we defined flow error measurement by combining three speed curves - (a) speed of hand marker moving, (b) speed of shoulder extension angle and (c) speed of elbow extension.

Denote the speed curve during reaching as *v(t)*. The zero crossing number *k* is defined as the number of zero crossing of first order derivative of speed *v'(t)*. The smaller the zero crossing number, the smoother the speed curves. Another useful metric is the curve fitting error that is defined as the square error e_f between original curve and fitting curve. Before computing the curve fitting error, we first normalize the curve by the maximum value. Then we divide the reaching duration into acceleration phrase and deceleration phrase due to the asymmetry of speed curve and fit the two phrases separately. Hence, the curve fitting error of speed is: $e_f = \int_{t1}^{t2} [v_N(t) - f(v_N(t))]^2 dt + \int_{t2}^{t3} [v_N(t) - f(v_N(t))]^2 dt$, where $v_N(t)$ is normalized speed curve, *t1*, *t2* and *t3* are reaction time, acceleration ending time, and deceleration time respectively, *f*() is curve fitting operator. The zero crossing number and curve fitting error were combined as a smooth vector to represent the smoothness of reaching speed.

The overall flow error incorporates the smoothness of three speed curves: (a) hand marker speed, (b) shoulder extension speed and (c) elbow extension speed. Define the smooth vector of hand marker speed, shoulder extension speed and elbow extension speed as M_h, M_s and M_e respectively. The overall flow error ***F*** is represented as the linear combination of these three smooth vectors: $F = w_1^f \cdot M_h + w_2^f \cdot M_s + w_3^f \cdot M_e$. Wherein, w_1^f, w_2^f and w_3^f are constant weight factors.

III. RESULTS

Six able-body normal subjects were recruited to test the system. The examples of abstract image feedback and musical feedback are shown in Fig. 3 and 4 respectively. Fig. 5 demonstrates the averaged spatial error, arm openness error, zero crossing number of velocity curve, and velocity curve fitting error across 6 subjects. Wherein, abstract II in Fig. 5 denotes the trials having additional musical mapping on arm openness, comparing with abstract I environment.

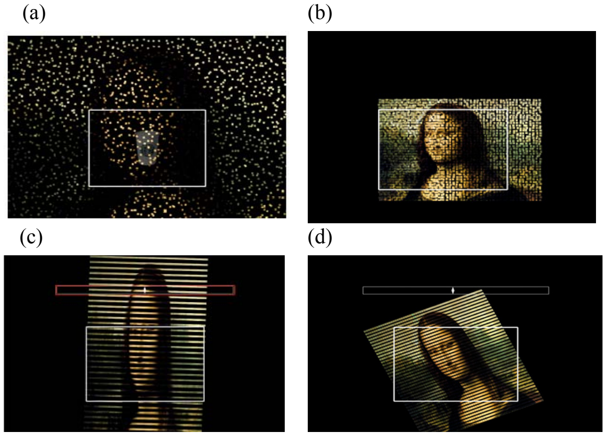

Fig. 3. The abstract image feedback. (a) Particles begin to the form the image as hand approaches the target. (b) Image pulled to the right when subject is off target. (c) Vertical bands appear when the subject has wrong target height. (d) Image rotate as hand orientation is off desired value.

The feedback is sensitive to movement state of subjects (Fig. 3 and 4). Adaptation is observed in curves in Fig. 5, i.e. error decreases. The result indicates that all subjects can perceive and understand multivariable feedbacks, then, control and adapt to more enriched abstract environment. The visual feedback with abstract image can guide subjects to provide almost the same spatial error as reaching in physical world (around 0.08 calculated by equation 1). The arm openness error in abstract IME II is relatively low because the arm openness was mapped into musical feedback. However, the number trial is too small and the task is too simple for normal subjects to provide any significant statistical result.

IV. CONCLUSION

This study demonstrates the novel concept and design of abstract IME based biofeedback system. Normal subjects were recruited to validate the environment design and measurements. The hypothesis of this design is that the feedback presented through forms different from real-life might reinforce more on senorimotor integration. In the future, an interesting study could be conducted to investigate if the abstract IME training is more effective than training in virtual environment simulating the real world on motor recovery that facilitates us to explore the efficient design of IME biofeedback system for neurorehabilitation.

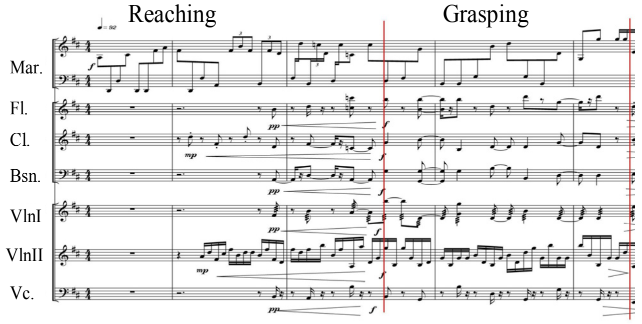

Fig. 4. Accompanying musical feedback while a normal subject reaching in the abstract environment. Mar. = Marimba, Fl. = Flute, Cl. = Clarinet, Bsn = Bassoon, Vln I = Violins group I, Vln II = Violine group II. Vc. =volincello.

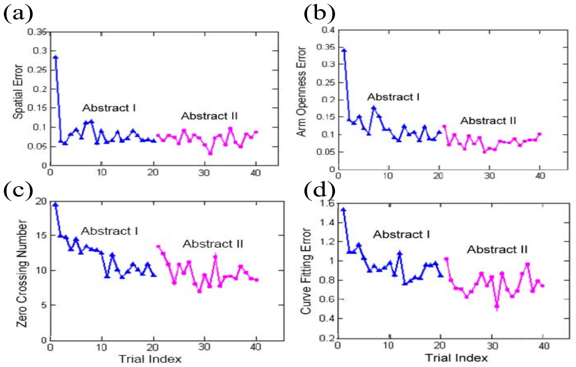

Fig. 5. Quantified measurement to assess the movement. All presented data are averaged across 6 normal subjects. (a) Spatial error, (b) arm openness error, (c) zero crossing number of velocity, (d) curving fitting error.

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