Validation of a novel personalized therapeutic virtual gaming system

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***Abstract*—The overall purpose of this study is to explore the potential of a personalized virtual gaming system to support and enhance treatment of children with cerebral palsy (CP). The iVG4Rehab system (Intelligent therapeutic Virtual Gaming System for Rehabilitation) is capable of dynamically adjusting game parameters in accordance with the abilities and therapeutic needs of its users. This paper presents the results of a validation study of typically developing children as a first step towards investigating its potential to enhance therapy for children with CP. The results demonstrated that the game was enjoyable, was not perceived to require excessive effort and was sensitive to changes in participant performance, particularly under conditions that were easy (accuracy mode with no weights) and that were more difficult (dwell mode with weights).**

***Keywords*—personalization, virtual game, typically developing children, cerebral palsy.**

I. Introduction

Cerebral palsy (CP) is the most common cause of motor disability in childhood [1]. It describes a group of developmental disorders of movement and posture leading to activity restriction that is attributed to disturbances occurring in the fetal or infant brain [2]. These impairments often have a negative effect on child's performance in basic daily activities, participation, self-care and quality of life.

In recent years, there has been an increase in the use of advanced technologies across a wide range of applications in the general area of health care and clinical practice [3]. A group of these technologies, referred to as virtual reality, refers to an interactive, high 'presence', real time gaming experience driven by the user's movements [4]. Virtual games appear to increase motivation, self-efficacy and playfulness, and leads to an increased sense of mastery [5, 6]. It provides a flexible and ecologically valid way to improve specific abilities within life-like simulations that are safe and motivating [6, 7, 8].

When virtual gaming is used in rehabilitation it facilitates the evaluation and practice of specific motor, cognitive and meta-cognitive skills in a stimulus-controlled environment that may be difficult to be delivered and controlled in the 'real-world' [9]. Using virtual games in therapy has been shown to be beneficial for children with CP, allowing a therapist to adjust the game setting and its difficulty level according to the child's abilities, needs and therapeutic goals [7].

Therapists may select specific characteristics of VR hardware, software and task complexity, to provide clients with more than just an engaging experience. The technology enables the grading of task complexity and control over different stimulus features such as size and color; the client can receive immediate feedback through different senses (e.g., visual, auditory, haptic, vestibular) while the therapist may intervene to provide additional challenges or assistance [10-12].

A meta-analysis looking at the effectiveness of virtual reality versus conventional therapy on upper extremity function of children with CP, identified 14 studies, including three randomized control trials and 11 case series [13]. The meta-analysis validated that VR had a potentially strong effect in improving the upper extremity function of children with CP. According to the meta-analysis virtual reality is a viable tool to improve UE function in children with CP. Implementing a laboratory-based VR intervention program using an engineer-built VR system for young children with CP seems to yield the most improvement in their UE function.

Despite the considerable progress in developing virtual games and examining their effectiveness, a fundamental limitation of many existing virtual systems is that stimuli and treatment protocols cannot be modified in real-time in response to changes in the child's performance [14]. To date, a therapist's control over the settings of the virtual environment is almost always limited to manual operation with the game level parameters set at the beginning of the therapeutic session. Any subsequently needed adjustments require a pause in game play so that the therapist can manually change them. This seriously limits the continuity of an intervention session since such off-line adjustments are often needed to account for changes in endurance, balance and coordination, limb range of motion, and cognitive and meta-cognitive abilities due to fatigue, emotional lability and pain [15]. In contrast, client abilities may also unexpectedly improve due to motivation or medication.

Thus, the ability of a virtual game to adapt itself to the changing performance of the child may better support overall training. The availability of a personalized VR system will allow clinicians to be more available and attentive to the client and provide therapy at just the right level of challenge to encourage motivation and engagement.

This study was funded, in part, by the Israel Center for Research Excellence: LINKS - Learning in a NetworKed Society

Research in the field of personalization of gaming environments for rehabilitation has emerged in recent years [16-18]. The main approaches to personalization are the Dynamic Difficulty Adaptation technique (DDA) [16, 17] and the semi-automatic difficulty adaptation approach [18]. DDA aims to dynamically compute appropriate challenges for users by maximizing their efforts without exceeding their abilities. Although this approach appears to be beneficial for therapy, it may prevent therapists from adjusting game parameters and therefore limits their ability to modify therapeutic strategies. To overcome this challenge, further studies have suggested the use of a semi-automatic difficulty adaptation approach [18, 19]. This allows therapists to monitor and adjust the activity by predefining several independent system parameters (e.g., selecting the exercises, difficulty level, time allocated for each exercise, number of repetitions and constraints on movements.

Although personalization of VR has been previously used for rehabilitation, most studies have targeted post-stroke rehabilitation. Moreover, the platform often used to implement personalization was tablet-based [16, 17]. Since it is valuable to perform upper extremity activities against gravity, personalization that is based on gesture recognition is important. Finally, in some prior applications of personalization, the parameters for each session were set in accordance with the user's performance in the previous session rather than being implemented dynamically in real-time [18, 20].

The objective of this paper is to present the results of a validation of a personalized virtual game prototype as used by typically developing children in order to identify its benefits as well as limitations. The results of this usability study are expected to contribute to the implementation of this approach for children with disabilities.

II. Methods

A. Participants

Sixty typically developing children, aged 6-10 years (29 boys, 31 girls; mean ± SD age = 7.8 ± 1.1 years) were tested during several 2-minute trials of a virtual game. All the participants were right handed, and all had previous experience in computer games, with 61.7% playing computer games several times a week and 28.3% playing computer games daily.

The children were recruited via snowball sampling, followed by a letter of explanation to parents of eligible children in order to seek their consent. Inclusion criteria were: typically developing children. Exclusion criteria: adverse health conditions, developmental delay, uncorrected vision impairment, neuromuscular dysfunction. Consent to carry out this study was obtained from the Institutional Review Board of the University of Haifa.

B. Instruments

1) iVG4Rehab: An intelligent Virtual Gaming system for Rehabilitation of children with motor disabilities.

Based on interviews and focus group discussions, an intelligent therapeutic virtual gaming system that adapts itself to the child's dynamic performance, the iVG4Rehab system (intelligent therapeutic Virtual Gaming system for Rehabilitation), was designed and developed in the C# and Unity 3D platforms. Microsoft's Kinect 2 sensor, an infrared light sensor, was used to track body movements without body markers or remote controls [21, 22] as represented in Fig.1. The general concept of the game is a simple 'reach to touch' task that is played using movement of the upper limbs while the user faces a large screen. The end-point position of the palm is used to indicate the event of reaching to a target with the hand.

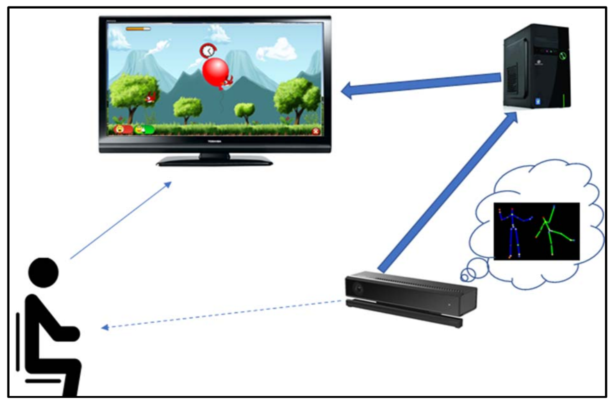

Fig. 1 shows a seated child facing the Kinect 2 and a 32 inch monitor displaying a virtual game, both at a distance of 1.5 m from the child.

Since iVG4Rehab is designed to accommodate children with varying levels of motor ability, including those with cerebral palsy, it has been programmed to calibrate each participant's range of motion (ROM) prior to the session. This is accomplished by mapping the upper extremity (U/E) ROM as the participant reaches for ball-shaped targets on the computer screen. Thus, the initial location of the target balloons in the subsequently played game appear in random order within an envelope defined during the mapping procedure, as illustrated in Fig. 2.

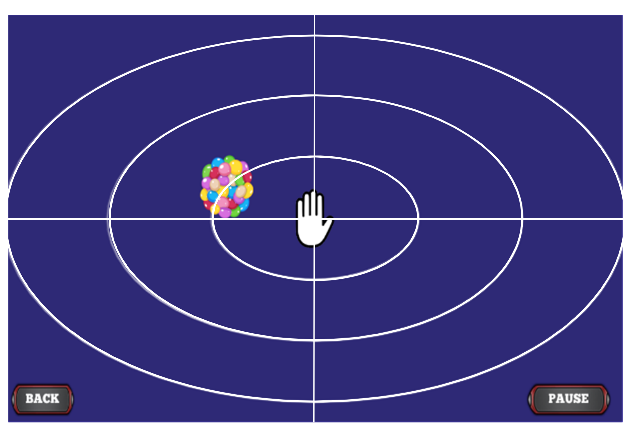

Fig. 2: Mapping feature

The system has two modes of operation: (1) a conventional, non-dynamic virtual game where it records a log of all events and (2) a dynamic mode, where the system adapts continuously to the user's performance. The personalized mode has two stages:

(a) Configuration and calibration where game parameters are set at the beginning of a session to adjust the system to the specific environmental conditions and personal abilities (e.g., user's joint range of motion, distance from the screen).

(b) Active game where the users interact with the game stimuli while the system monitors their achievements based on the data collected during the session including the user's kinematic performance (U/E end point positions measured by the Kinect 2) and game results (target position and the success/failure of the user to reach them).

The system monitors the child's performance, using appropriate learning and reasoning mechanisms to update the user model based on personal information, such as the user's age, education, preferences, past interactions with the system and game performance. The user model is continuously monitored and updated via an algorithm that compares current game parameters, recorded user performance and game success (ability to hit target stimuli) [23]. Thus, personalization occurs in real time according to the observed child's behavior and adjusts the parameters of the activity in accordance with the child's abilities. The game parameters are dynamically adjusted as needed (e.g., in recognition of user fatigue or ability beyond what was initially anticipated) include: (1) Accuracy of reaching displayed target and (2) Ability to sustain position on target. These parameters are automatically adjusted according to pre-defined criteria of success.

The 'accuracy' parameter is graded by decreasing (increasing) the size of the virtual targets (in this case, balloons) following three successive hits (misses). The sustained position variable is graded by changing the time during which the user has to 'hover' ('dwell') over the target for three successive hits (misses).

The 'Balloon' game, shown in Fig. 3, was developed for prototype usability testing. The user's arm movements control the position of a bird-shaped avatar to 'pop' virtual balloons that float in the sky when the former align with the latter. In dwell mode, the bird-shaped avatar must hover over each balloon for a predefined period (ranging from 0.5-3.0 s); feedback is displayed by an on-screen progress circle which shows time the balloon pops. This mode was designed to encourage the child to engage in a sustained position task. In the accuracy mode, the virtual balloons pop as soon as the participant's arm moves the bird-shaped avatar to align with each successive balloon.

Fig. 3: A child using the 'iVG4Rehab' system

2) Usability outcome measure

Responses to two items from the Short Feedback Questionnaire – Child (SFQ-Child) [24] were recorded on a 5-point Likert scale with variations of 'smiley' icons denoting 1 (not at all) to 5 (very much). A visual version of the questionnaire that was adapted for children was used. The first item queried the participant's enjoyment of the activity.

3) Performance outcomes

- Changes in game levels throughout the 120 s game.
- X,Y, Z coordinates of the end point of the user's palm to generate the arm movement trajectories. The total pathway in meters is calculated from these data.

4) Weights

The current usability study tested the prototype while typically developing children played the personalized game with and without two 500 g wrist weights, one on each arm. The primary reason for testing game play with added weights was to ensure that the game would be difficult enough to require changes in game levels (increases and decreases) so that the functionality of the personalization routine could be tested.

C. Procedure

Informed consent was provided by a parent who also completed the demographic questionnaire. The child was seated on a chair facing the Kinect 2 camera and a 32 inch monitor, both located at a distance of approximately 120cm. Following a demonstration of the game, the child's U/E ROM was mapped and recorded in the system. Initially, the participants played a 60 s trial of the conventional version of iVG4Rehab i.e., without performance-dependent changes in levels of difficulty but with ROM set to their own abilities.

iVG4Rehab was then played in dwell mode, first as a conventional game and then as a personalized game, for 120 s each. It was then played again in dwell mode for

120 s, this time with the 500 gm wrist weights. Finally, the personalized game was played in accuracy mode for 120s.

Following each game, the participant was asked the two usability questions on enjoyment and effort. They then had a 120 s break during which time they played the 'fruit ninja' game on an iPad.

D. Data Analysis

Data analysis was conducted with the Statistical Package for the Social Sciences (SPSS: version 25). Descriptive statistics for study's population were performed. Paired sample T-tests was used to compare changes in game levels between the personalized game when played with and without weights and to compare differences in total trajectories of the hand movement between the personalized and conventional games when played in dwell mode. The nonparametric Wilcoxon test was used to compare perceived effort and enjoyment while playing the personalized and conventional games.

III. RESULTS

We first illustrate changes in game level for a representative participant aged 8 years who is typically developing. As expected, there were no changes in level when playing the conventional game, either in dwell mode with no weights (CG-D$_{NW}$) or dwell mode with weights (CG-D$_W$). In contrast, as shown in Fig. 4, there were changes in level during the personalized game when played in dwell mode with (PG-D$_W$, green line) and without weights (PG-D$_{NW}$, blue line). The levels during PG-D$_{NW}$ increased to a maximum of level 3 with a single decrease at the beginning of the game and, indicative of improved performance by this participant. During PG-D$_W$, when the personalized game was played with weights, fewer increases were demonstrated, and the final level reached was 1. The red line portrays changes in levels when the personalized game is played in accuracy mode without weights (PG-A$_{NW}$) for the same participant; here we note the rapidly and continuously increasing levels to a maximum = 4.

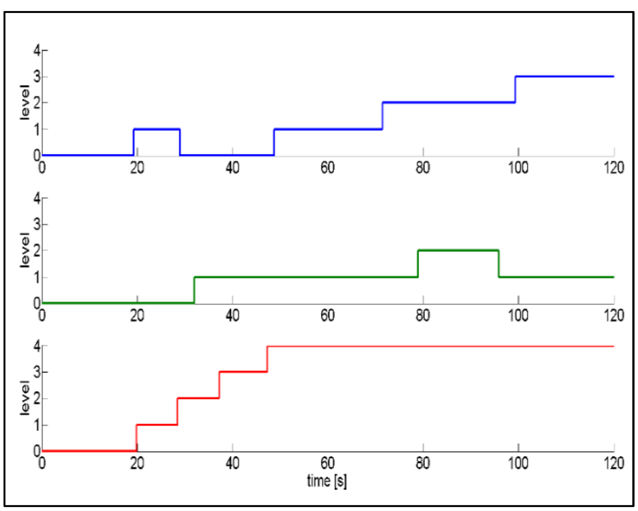

Fig. 4. Changes in game level during the personalized game in dwell mode without weight (PG-D$_{NW}$, blue line), personalized game in dwell mode with weight (PG-D$_W$, green line) and personalized game in accuracy mode without weight (PG-A$_{NW}$, red line).

Table 1 presents mean game level changes for all participants when the personalized game was played in dwell mode with and without weights. The mean number of increases were significantly higher during PG-D$_{NW}$ (3.32±0.7) than PG-D$_W$ (2.98±0.77, t=2.6, p=0.01) and the mean number of decreases were significantly lower during PG-D$_{NW}$ (0.87±1.04) than during PG-D$_W$ (1.25±1.21, t=-2.2, p=0.03). That is, participants were increasingly successful when playing in dwell mode without weights and less and less successful when playing in dwell mode with weights.

TABLE 1: GAME LEVEL CHANGES

Number game level changes	***PG-D$_{NW}$ Mean ± SD***	***PG-D$_W$ Mean ± SD***	***t***	***p***
Total	2.09 ± 1.51	2.11 ± 1.33	6.64	0.95
Increases	3.32 ± 0.7	2.98 ± 0.77	2.61	0.01*
Decreases	0.87 ± 1.04	1.25 ± 1.21	-2.21	0.03*

*PG-D$_{NW}$: personalized game in dwell mode without weights; PG-D$_W$: personalized game in dwell mode with weights. * denotes significant differences.*

The X, Y, and Z coordinates for virtual markers on the palms of both hands were recorded throughout each game and used to calculate the trajectories as the targets were displayed. Fig. 5 shows a 2D plot (X and Y) of these trajectories for a representative, typically developing participant's hand while playing a personalized game in dwell mode without (PG-D$_{NW}$, upper panel) and with (PG-D$_W$, lower panel) weights. The red and blue lines show the right-hand and left-hand trajectories respectively. The light dashed circles mark the cursor location when each target was hit while the dark solid circles show the target locations (i.e., the virtual balloons). A target hit is recorded when these two circles overlap.

As indicated by the overlap of the two circles in the upper panel, all targets were hit in this example. The pathways appear to be relatively straight, and the overshooting of the targets appear to be small. During play with weights, on the contrary, four targets (# 6, 7, 8 and 9) were missed and the pathways were much more complex. The total distance traversed during PG-D$_{NW}$ was lower (left hand = 21.9 m, right hand = 22.9 m) was considerably less than the distance traversed during PG-D$_W$ (left hand = 27.6 m, right hand = 27.4 m). The analysis for the entire sample is currently underway.

The participants' perceived effort was significantly lower while playing the personalized game in dwell mode (PG-D$_{NW}$: mean ± SD= 3.83±0.72) compared to playing the conventional game in dwell mode (CG-D$_{NW}$: 4.71±0.63, z=-5.21, p=.000) but there were no significant differences in their perceived enjoyment while playing these two versions of the game (PG-D$_{NW}$: 4.69±0.54 and CG-D$_{NW}$: 4.83±0.42, z=-1.5, p=.13).

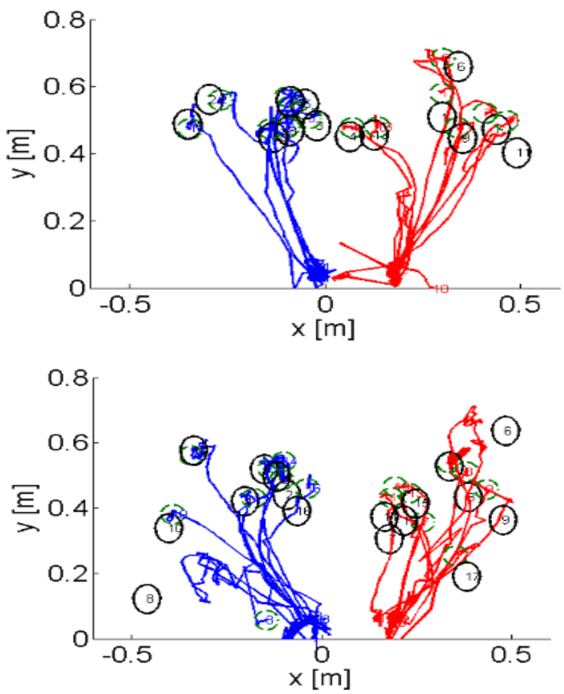

Fig. 5. X-Y trajectories during the personalized game without weights (upper panel) and with weights (lower panel) for a representative child with typical development. Motions of both the left hand (blue) and right (red) arms are shown.

IV. Discussion

Personalized virtual systems aim to address clients' changing abilities and adjust the difficulty of the activity to both their baseline abilities and to changes in performance due to improvement (e.g., driven by the therapeutic intervention) as well as to any deterioration as may occur, for example, upon fatigue [14]. The current study documented the usability of the personalized iVG4Rehab game for typically developing children as a first step towards investigating its potential to enhance therapy for children with CP. The results demonstrated that the game was enjoyable, was not perceived to require excessive effort and was sensitive to changes in participant performance, particularly under conditions that were easy (accuracy mode with no weights) and that were more difficult (dwell mode with weights).

A key element in designing virtual games for children with motor impairments is ensuring that they are responsive to challenges associated with reduced tolerance to fatigue due to muscle weakness and/or limitations in joint range of motion [6]. In addition, the clinical literature strongly supports the need for rehabilitating clients at levels that are "just beyond" their current comfort zone in order to elicit remedial responses [25]. Virtual games appear to be a valuable tool in therapy, since they allow a therapist to adjust the game setting and its difficulty level according to the child's abilities, needs and therapeutic goals [7]. Therapists may select specific characteristics of VR hardware, software and task complexity, to provide clients with more than just an engaging experience [26].

This need to adjust the difficulty of the activity to a client's dynamic performance and progress in real time is the essence of "personalization". A personalized VR rehabilitation system is one that addresses the client's changing abilities and provides an optimal training program in an automated manner [14]. Research in the field of personalization of gaming environments for rehabilitation has begun to emerge in recent years [16-18]. These studies have emphasized the benefits of personalization for rehabilitation not only to maintain the player's motivation but also to ensure the achievement of learning and training objectives.

Typically, children without impairments are readily able to succeed in playing such games at the highest levels and thus are not ideal candidates to serve as practical beta-testing subjects for studies of usability and validity. On the other hand, there is some concern about the ethical acceptability of testing children with disabilities on a platform that is still under development. The compromise used in the current study was to make the task more challenging by adding weights to each arm of the typically developing participants while they played the game in the dwell mode that was otherwise almost effortless for them. It is clear that adding weights to typically developing children does not replicate the difficulties experienced by children with cerebral palsy when performing U/E reaches of the type required by the current virtual game. Their motor difficulties including difficulties in postural control, balance and movement are usually due to disorganized and delayed development of the neurological mechanisms [27].

Although our intent was not to model CP, we note that simulating an impairment by adding weights is a known paradigm in the field of health science. For example, Hides et al. [28, 29] used simulated weight-bearing in a study of healthy adults to assess recruitment of the abdominal muscles during static simulated weight-bearing task. Results showed increases in muscle mass in response to simulated weight-bearing.

The focus of this paper has been on the usability results including participant ratings of enjoyment and effort as well as performance results including changes in game level. When asked about a game's level of difficulty, children reported that they exerted more effort in the personalized game compared to the conventional game. Nevertheless, when asked about their enjoyment, no significant differences between the personalized and conventional games were found. Thus even though the participants exerted more effort during the personalized game, and perceived that they did so, this did not detract from their enjoyment. The challenge of the more difficult, yet achievable, game may have enhanced the participants' motivation which is known to play a crucial role for compliance with therapy [30-32]. This finding is of clinical importance since maintaining a high-level of motivation while participating in a demanding and challenging task is recognized as a key advantage of personalized virtual gaming system in therapy.

ACKNOWLEDGMENTS

The authors thank Baha Ganayim who designed and coded an initial prototype of the personalized virtual game system, Rana Abbas who participated in the data collection and Sandra Zuckerman who provided support for the statistical analysis. ST was funded by a doctoral scholarship from the University of Haifa.

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