JMIR Serious Games

Journal Impact Factor (JIF) (2023): 3.8
Volume 5 (2017), Issue 3 ISSN 2291-9279 Editor-in-Chief: Gunther Eysenbach, MD, MPH

Contents

Original Papers

Original Paper

Rehabilitation-Oriented Serious Game Development and Evaluation Guidelines for Musculoskeletal Disorders

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Abstract

Background: The progress in information and communication technology (ICT) led to the development of a new rehabilitation technique called "serious game for functional rehabilitation." Previous works have shown that serious games can be used for general health and specific disease management. However, there is still lack of consensus on development and evaluation guidelines. It is important to note that the game performance depends on the designed scenario.

Objective: The objective of this work was to develop specific game scenarios and evaluate them with a panel of musculoskeletal patients to propose game development and evaluation guidelines.

Methods: A two-stage workflow was proposed using determinant framework. The development guideline includes the selection of three-dimensional (3D) computer graphics technologies and tools, the modeling of physical aspects, the design of rehabilitation scenarios, and the implementation of the proposed scenarios. The evaluation guideline consists of the definition of evaluation metrics, the execution of the evaluation campaign, the analysis of user results and feedbacks, and the improvement of the designed game.

Results: The case study for musculoskeletal disorders on the healthy control and patient groups showed the usefulness of these guidelines and associated games. All participants enjoyed the 2 developed games (football and object manipulation), and found them challenging and amusing. In particular, some healthy subjects increased their score when enhancing the level of difficulty. Furthermore, there were no risks and accidents associated with the execution of these games.

Conclusions: It is expected that with the proven effectiveness of the proposed guidelines and associated games, this new rehabilitation game may be translated into clinical routine practice for the benefit of patients with musculoskeletal disorders.

(JMIR Serious Games 2017;5(3):e14) doi:10.2196/games.7284

KEYWORDS

rehabilitation exercise; virtual rehabilitation; rehabilitation; user computer interface; musculoskeletal diseases

Introduction

Context

Musculoskeletal disorders lead to high medical costs all over the world. These disorders affect the working performance and well-being of the involved people [1,2]. Age-related deficiencies, sport and transport accidents, and genetic conditions are the main sources of these disorders. In the United States, billions of dollars have been spent for treatment and patient management. In Europe, the ageing effect of the population requires significant efforts for medical experts and infrastructures. Research studies have been performed to provide better diagnosis and treatment of these disorders. Among the most common routine practices, functional rehabilitation plays a key role in the recovery of mechanical functions of the human body. This specific treatment helps recover the functionality of the musculoskeletal system by improving the ranges of motion as well as the muscle strengths. Current physical therapy programs are performed by patients and supervised by medical doctors over a long period of time in hospitals or clinics [3,4]. This traditional rehabilitation scheme requires permanent involvement of different medical actors (eg, physiotherapists and medical doctors) during the program, leading to a high cost for medical human resources. Moreover, due to the repetitive nature of the rehabilitation exercises, the motivation of the patient decreases rapidly during the execution of the program. Recently, the progress in information and communication technology (ICT) led to the development of a new rehabilitation scheme called "serious game for functional rehabilitation" [5-7]. In fact, the coupling of the game technologies and functional rehabilitation allows a better interaction between patient and the rehabilitation program [8]. Moreover, the use of serious game scenarios may be a potential solution to improve the patient's motivation in future rehabilitation sessions.

State of the Art

Some research studies focused on games that could improve general health for adults and elders. Chen et al (2012) developed a lower limb power rehabilitation system. Each user needs to execute a squat motion, with sufficient power, to correctly build a virtual tower made of blocks [9]. The system was tested with 20 participants, whereas 20 control participants executed normal exercises for 6 weeks. The results showed that the participants using the developed system achieved greater improvements in power and velocity of movement. Sun et al (2013) presented a balance rehabilitation system using Kinect and a force plate [10]. The objective of this game was to fit an avatar in a specific frame indicated on the screen, while standing on the force plate. In total, 23 healthy subjects tested this system, but the results showed that different evaluation methods could lead to different interpretation of the player experience. Chatzitofis et al (2015) [11] implemented a home-based rehabilitation system for cardio vascular diseases using Kinect and body worn inertial sensors. The users need to start the game by warming up, and then they need to execute the assigned movement. Visual feedback is generated on the screen to help the user to optimize the movement. The system was evaluated with 6 patients. Finally, Lozano-Quilis et al (2014) [12] implemented an augmented reality system for multiple sclerosis using the Kinect. The system is called RemoviEM and includes 3 game exercises (TouchBall, TakeBall, and StepBall). In total, 11 patients tested the ability of the system to encourage players to perform exercises. The results were collected through a questionnaire and showed that patients accepted the system and felt safe and secure while playing.

Parkinson disease has been a subject of interest among serious game projects. Yu et al (2011) [13] developed a real-time Parkinson mediated rehabilitation environment. They implemented a system applied in a clinical space to treat Parkinson disease symptoms by improving the patient's ability to reach and step as far and as fast as possible. Patients are required to execute repetitive and variable tasks in order to learn new movement patterns and to perform the transition from one movement to another by performing mixed and multiple tasks. A virtual avatar is shown on the screen that mimics the patient's movements. However, the system was never tested on Parkinson disease patients. Assad et al (2011) also investigated the use of serious games for Parkinson disease patients, and they implemented a series of games that use the Sony PlayStation EyeToy as a motion capture tool [14]. Four different Parkinson disease adapted games were developed and tested by 13 Parkinson disease patients. The system was rated using a questionnaire completed by the patients after performing the exercises. This study concluded that the patients enjoyed the exercises. Paraskevopoulos et al (2014) developed serious games adapted to Parkinson disease patients [15]. They defined a guideline to successfully design serious games adapted to Parkinson disease through a detailed literature review of related works, and developed 2 games using the Wii Mote and the Kinect camera. They tested the games on 5 Parkinson disease patients and concluded that serious games have the potential to increase the level of engagement for such patients.

Another rehabilitation field that has been studied is stroke rehabilitation. Cho et al (2014) developed a proprioception rehabilitation system for stroke patients [16]. The user moves a connected cylinder to interact with the game. The objective was to hold the connected cylinder under a table to move the virtual cylinder from an initial position to a destination position. The study was tested with 10 healthy subjects and 10 stroke patients and showed significant improvement in patients. However, this improvement might have been attributed to patients becoming accustomed to the game. Another system used a commercial Wii Fit game and 2 Wii balance boards to adapt the games to stroke survivors [17]. Each balance board captures the center of pressure of the leg. The weak leg's signal is multiplied by a higher weight than the healthy leg's signal so that the patient applies more load on the weak leg. The system was tested on 3 stroke survivors (2 participants and 1 control) and showed that after 7 to 12 sessions, the patients began to rely more on their weak legs and began to tend to normal load ratios observed in healthy subjects. Ibarra Zannatha et al (2013) also developed a serious for game stroke rehabilitation using the Kinect camera, electromyography (EMG) sensors, and a humanoid robot [18]. The system consists of 4 games for the upper limbs. This system was not tested on stroke patients.

Literature showed that serious games have been intensively developed for general health and specific disease management. One of the most important aspects of serious games is the game playing scenario to motivate the patient. Moreover, user acceptability also plays an important role in promoting this new technology to clinical practice. Finally, the user security aspect needs particular attention to avoid new clinical complications for patients. Different game systems have been developed and tested. There is still lack of development and evaluation consensus guidelines to achieve these important aspects. It is important to note that the game performance depends on the designed scenario. Some authors have attempted to propose specific guidelines for game development-based learning [19] or for Parkinson disease rehabilitation [15]. However, methodologies and best practices related to the development of customized serious games for musculoskeletal disorders to recover complex joint and muscle functions are still lacking. Thus, the objective of this work was to develop specific game scenarios and to evaluate them with a panel of musculoskeletal patients, to propose game development and evaluation guidelines. In particular, specific games for the functional rehabilitation of musculoskeletal disorders were developed and evaluated using the proposed approach. Hence, the usefulness of the developed games was quantified. Discussion on the usefulness of the proposed guidelines according to the literature was also provided.

Methods

Development of Serious Games

The development of serious games for functional rehabilitation of musculoskeletal disorders is a complex engineering task. To deal with such complexity, a two-stage workflow was proposed. The first workflow relates to the development guideline (Figure 1), whereas the second workflow concerns the evaluation guideline (Figure 2). The development workflow includes the selection of three-dimensional (3D) computer graphics technologies and tools, the modeling of physical aspects, the design of rehabilitation scenarios, and the implementation of the proposed scenario. This workflow aims to design fun but useful game scenarios to motivate end users to perform functional rehabilitation tasks. The evaluation guideline consists of the definition of the evaluation metrics, the execution of the evaluation campaign, the analysis of user results and feedbacks, and the improvement of the designed game. Finally, the improved game is reevaluated in a closed-loop technique. This user-centered game design approach allows different users (eg, patients and medical experts) to participate actively in the design and evaluation stages. Note that the second workflow focuses on the evaluation of user acceptability and security aspects when using this new technology. The development of these guidelines was performed using determinant framework [20]. This theoretical approach has been commonly used to determine what important factors influence implementation outcomes. Thus, eight determinants (3D computer graphics technologies, physics modeling, scenario design, implementation, evaluation metrics definition, evaluation campaign, user result and feedback analysis, and game improvement) were hypothesized to influence the implementation outcomes of the development and evaluation of rehabilitation-oriented serious games. In fact, these components aim to cover necessary methodologies and best practices for developing customized serious games for musculoskeletal disorders and evaluating them. The choice of these components is based on our experiences gained from literature analysis and also from our preliminary studies on functional rehabilitation using serious game technologies [7,8].

Figure 1. Rehabilitation-oriented serious game: development guideline.

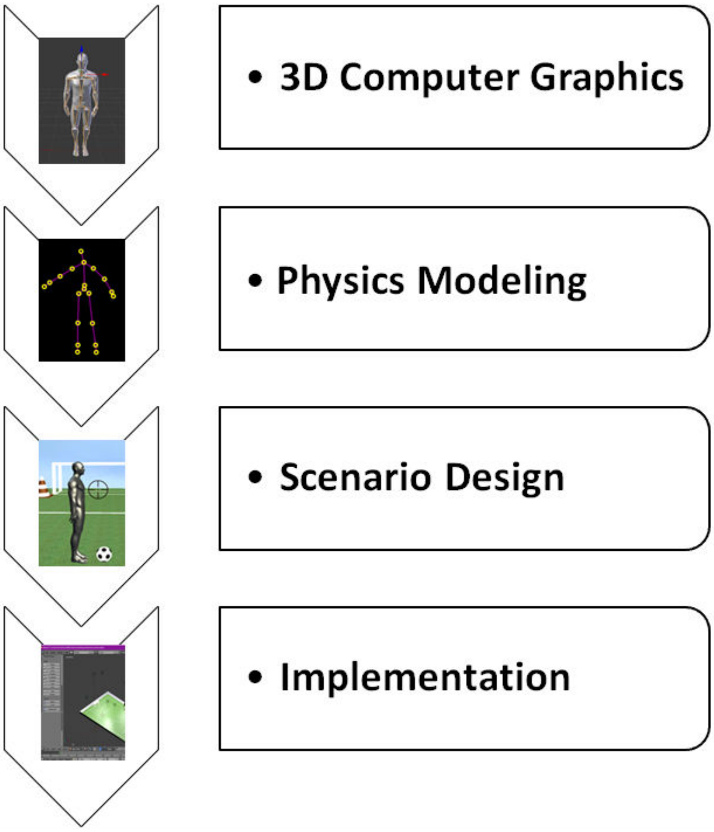
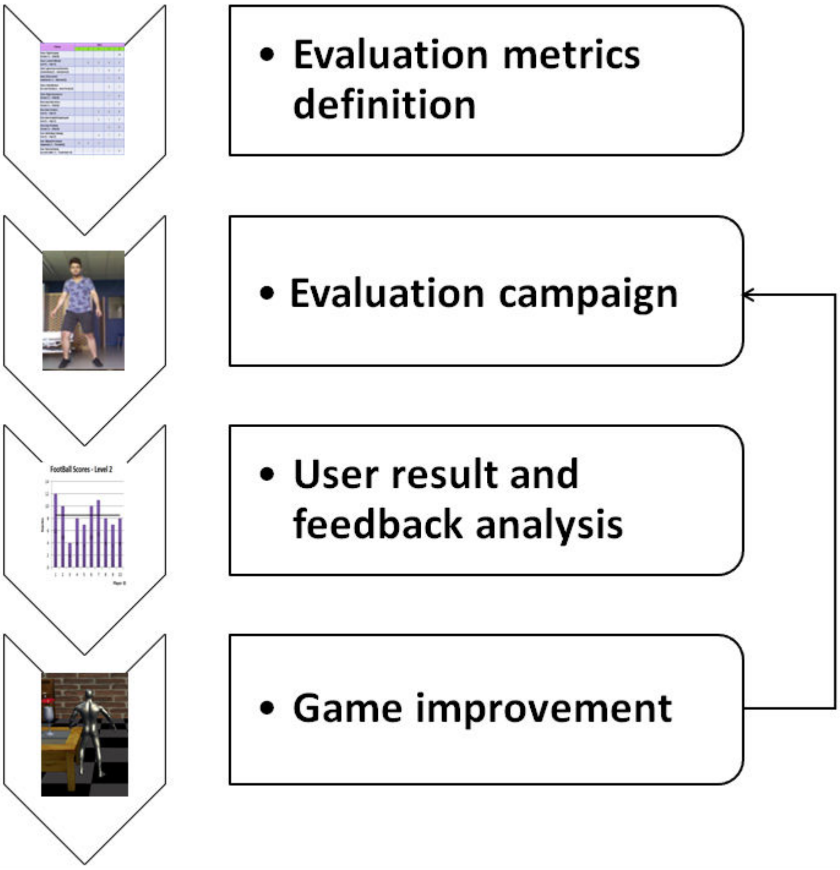


Figure 2. Rehabilitation-oriented serious game: evaluation guideline.



Case Study for Musculoskeletal Disorders

Rehabilitation-Oriented Serious Game: Development Guideline

This subsection describes the work done using a proposed development guideline for creating specific serious games for functional rehabilitation of musculoskeletal disorders.

Three-Dimensional (3D) Computer Graphics Technologies and Tools

The selection of available computer graphics technologies and tools plays a crucial role in the success of the rehabilitation game. To ensure a user-friendly, human-system interaction, cutting-edge technologies benefiting the most recent progress of ICT solutions need to be used. In this study, open source Blender design software (Neo Geo) was selected for human body modeling. XNA Game Studio (Microsoft) was selected as game engine. Microsoft Kinect camera was selected as human motion capture tool. Computer screen was used as human-system interface. The pertinence of these technological choices has been proven in our previous studies [7-8,21].

Physics Modeling

A 3D avatar model was developed using Blender design software to represent the human body. This is a 3D surface mesh model including a collection of vertices, edges, and faces that defines the external shape of the human body. Moreover, an internal skeleton structure was also created to define body segments (eg, thigh and leg) and their interaction (eg, joint) during the motion [21]. Game environments and interaction objects were also designed and implemented using Blender design software.

Games with 3D interactive objects need to establish interaction rules between them. An algorithm was designed and implemented to detect collisions between objects within the scene. The challenge was to find a way to differentiate between the detection between different avatar bones and 3D objects; therefore, we created spheres around each bone of the body (Figure 3. Note that the radius and positions of these spheres are adjustable to a specific subject body. The assessment of the collisions is done by calculating the distance between the spheres of objects and bones (Figure 3).

Let S_1 be a sphere with a 3D center $C_1(C_{1x}, C_{1y}, C_{1z})$ and a radius r_1, and S_2 another sphere with center $C_2(C_{2x}, C_{2y}, C_{2z})$ and radius r_2. The distance between the 2 centers of the 2 spheres is d drawn in Figure 3 and is computed using the following equation:

$$d=[(C_{1x}-C_{2x})^2+(C_{1y}-C_{2y})^2+(C_{1z}-C_{2z})^2]^{1/2}$$

This distance is computed between every 2 objects at each updated iteration during the game. If d is found to be less than the sum of the 2 radiuses r_1 and r_2, a collision is detected, and the game reacts to it by a certain preprogramed reaction.

Scenario Design

Two task-oriented game scenarios (football and object manipulation) were designed and implemented. The football game aims at practicing body orientation and lower limb motions, allowing the rehabilitation of spinal and lower limb systems. The object manipulation aims to practice the upper limb and lower limb motions with a focus on the detailed hand skill. The description of each game is given in the following paragraphs.

Football Game

This game requires the player to execute many consecutive gestures. First, players have to stand in front of the Kinect and the computer screen. Then, they need to target the left or right cones by pivoting their body (Figure 4). Once the target is reached, the player has to verify that the pointer in the bottom right corner of the screen is in the green zone. If the pointer is green, they kick the ball to hit the cone and score one point. Otherwise, if they kick while the pointer is red, the ball will miss. When the cone is hit, the user needs to pivot back to the original position to get another ball. A point is awarded for every cone hit. We developed three levels of difficulty because patients playing the game might be in different phases of their rehabilitation. Using the different developed levels, experts can configure the difficulty of the exercises to be executed by their patients according to the rehabilitation progress. In the easy level, the cones are big and the green or red pointer is slow. The medium level decreases the size of the cones. Finally, to make it harder, the pointer will move faster on the hard level. Experts can also define the duration for each exercise, which gives them more control over the rehabilitation program. This game aims at the rehabilitation of several parts of the body. It targets balance, since the users rotate to target a cone. In addition, it includes a decision-making action, since players have to verify the pointer position. Finally, the lower limbs are also affected, since the patient has to kick the ball. It is noted that a soccer stadium was designed for this specific rehabilitation game.

Object Manipulation Game

In this scene, the user needs to take a flower from the given vase and put it in the other one (Figure 4). They repeat the same actions from right to left until the game-time expires. Three levels of difficulty (easy, medium, and hard) are defined. In the first level, the virtual avatar is fixed between 2 tables and can only move their hands. In particular, the player is rewarded 4 points for a combination of 3 successive gestures: take the flower with the first hand from the first vase, switch the flower to the second hand, and put the flower in the second vase. The second level of this game requires the player to move left and right while a certain distance separates the tables. Therefore, players have to move one step left and then get the flower. They switch it to the other hand and then move one step to the right in order to put the flower in the other vase. Finally, the third level of difficulty is similar to the second one but the challenge is to put the flower in the other vase before the expiration of a timer that appears on the bottom of the screen. This game targets several parts of the body. The upper limbs are targeted in all the levels, whereas the lower limbs are targeted only by the second and third levels. Moreover, the third level targets lower limb movement speed recovery, since the timer would force the users to move quicker. It is noted that a surrounding living room was designed for this specific rehabilitation game.

Implementation

Visual Studio.Net, with C# programming language, was adopted for image acquisition and processing, body tracking, object manipulation, as well as for the development of graphical user interfaces (GUIs).

Figure 3. Illustrations of the association of collision spheres to avatar bones (a) and object collision detection principle (b).

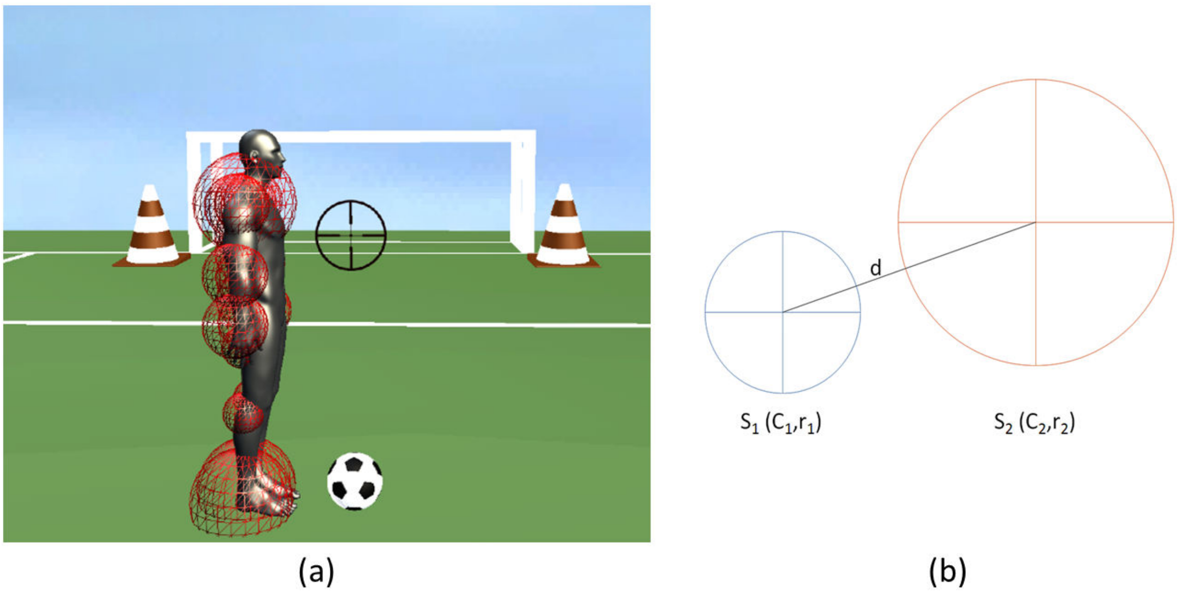
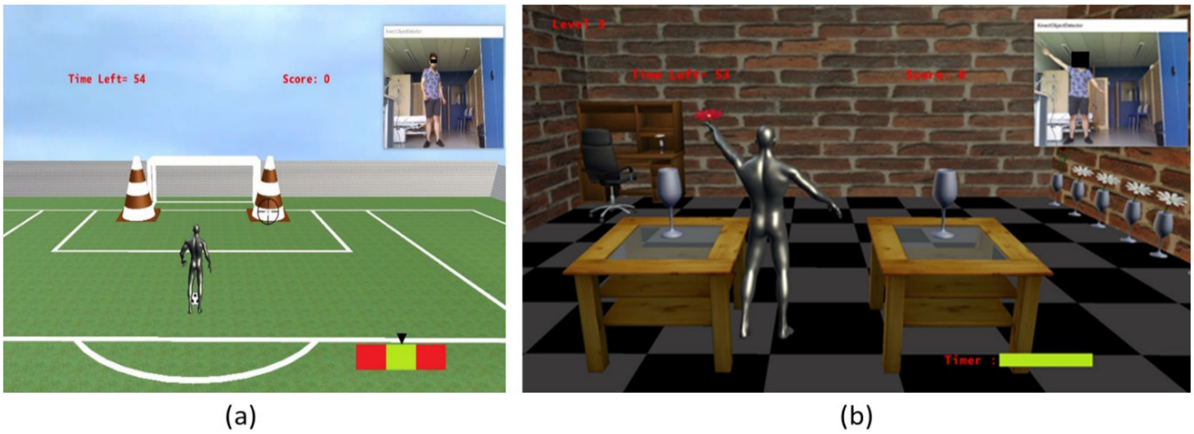


Figure 4. Football game (easy level) (a) and object manipulation game (hard level) (b).



Rehabilitation-Oriented Serious Game: Evaluation Guideline

This part presents the work done, as well as outcomes issued from the application of the proposed evaluation guideline for assessing the developed games.

Definition of Evaluation Metrics

The game-playing performance was evaluated by the points acquired at the end of each scenario. For the usage acceptability aspect of the designed games, a questionnaire was defined. At the end of each game scene, players were required to fill out a questionnaire. The questionnaire consists of 13 questions for each specific game scenario. The feedback focuses on the game, exercise, and user aspect. For the game, the objective, the level of difficulty, the ignorance of achievement, the attractiveness of the 3D environment and GUI, and the game management (begin, end) were investigates. For the exercise, the game instructions, the variation of scenarios, the suitability of the game to the goal, and the clearness of the feedback were examined. For the user, the motivating challenge, the possibility to make mistakes, and the security feeling were investigated.

Evaluation Campaign

The developed game scenarios were evaluated by a normal healthy group (10 subjects: 6 males and 4 females with a mean age of 26.8 [standard deviation, SD 5.65]), to ensure the security condition, and then evaluated by a population of 20 pathological subjects (13 males and 7 females with a mean age of 49.75 [SD 18.68]) at the "Centre Hospitalier Universitaire de Limoges" (France). The patient group included different musculoskeletal disorders (3 amputee patients, 8 hemiplegia patients, 1 hereditary spastic paraplegia patient, 1 patient with ankle arthrodesis, 1 stroke patient, 1 patient with shoulder capsulitis, 1 patient with low back pain, 1 patient with carpal tunnel, 1 patient with prosthesis, 1 patient with muscle disease, and 1 patient with walking difficulty due to a car accident). Each participant signed an informed consent agreement before playing the rehabilitation games. It is important to note that the execution of rehabilitation serious game was monitored by clinicians, to ensure the ability and the security of the patients when using this new rehabilitation tool. Each healthy subject was asked to play every level of difficulty of each game, which means a total of 6 trials per subject. Some patients were not able to try all levels or even one of the two games due to the severity of their state (amputation, leg prosthesis, and paralyses). Medical experts were given the decision to accept or decline the participation of their patient in a game or a level of a certain game. Therapists accompanied their patients by standing behind them and supporting them, to ensure their security. The duration of each game level was around 60 seconds. A rest time of around 2 min was also allowed for each participant when necessary (ie, recovery from fatigue) after each game execution. The total time of the test for one subject was equal to 20 min approximately.

Results

User Result and Feedback Analysis

For the control group, the scores did not change so much when increasing the level of difficulty for the football scenario (Figures 5-7). The mean and SD scores of the easy, medium, and hard levels were 8.5 (SD 1.8), 8.5 (SD 2.2), and 8.5 (SD 2.7), respectively. Maximal scores were 11, 12, and 13 for the easy, medium, and hard levels of difficulty, respectively. Note that when a score is achieved, this means that the player finished a game with all requirements. Statistical test (*t*-test, implemented in Matlab R2010b software [The MathWorks Inc.]) showed no significant difference. In particular, some subjects (ID4 or ID6) increased their score when enhancing the level of difficulty. According to the healthy control group, the performance of the pathological population was significantly (*t*-test, $P<.005$) lower for all levels of difficulty (Figures 5-7). The mean and SD scores of the easy, medium, and hard levels were 2.7 (SD 1.3), 2.5 (SD 1.7), and 3.9 (SD 1.8), respectively. Maximal scores were 6, 6, and 7 for the easy, medium, and hard levels of difficulty, respectively. In particular, some patients (ID17 or ID24) increased their score when enhancing the level of difficulty. However, the number of the patients able to perform on harder levels was reduced from 19 patients for easy level to 8 patients for the hard level.

Regarding the object manipulation game, the same results were noted (Figures 8-10). The normal population showed mean and

SD scores of 51.6 (SD 13.3), 59.2 (SD 14), and 60.4 (SD 25) for the easy, medium, and hard levels, respectively. Maximal scores were 72, 88, and 116 for the easy, medium, and hard levels of difficulty, respectively. The pathological population showed mean and SD scores of 22.8 (SD 12.3), 22 (SD 12.2), and 25.3 (SD 21.7) for the easy, medium, and hard levels, respectively. Maximal scores were 52, 44, and 68 for the easy, medium, and hard levels of difficulty, respectively. Thus, the performance of the pathological population was significantly (*t*-test, $P<.05$) lower than that of the normal population. The number of the patients able to perform harder levels was also reduced from 17 patients for the easy level to 5 patients for the hard level.

For the responses to the questionnaires, 29 users (patients and healthy subjects) rated the football game, and 27 rated the object manipulation game.

Regarding the user acceptability of the evaluated games, all healthy subjects found the 2 developed games motivational, attractive, and challenging. A synthesis of the patients' responses to the football game questionnaire is depicted in Table 1. Moreover, they enjoyed all the levels of difficulty. Note that the answers about the accuracy of the human movements' detection varied. That can be interpreted by the limitations of the Kinect due to occlusion of limbs, which could affect the accuracy of movement detection. Most of the participants assumed that they were comfortable with the system, whereas some patients, having balance disorders, worried about some levels of difficulty. Finally, there were no risks and accidents associated with the execution of these 2 games not only for the normal population but also for the pathological population.

Figure 5. Game performance: patient group vs. healthy control group: easy level of the football scenario.

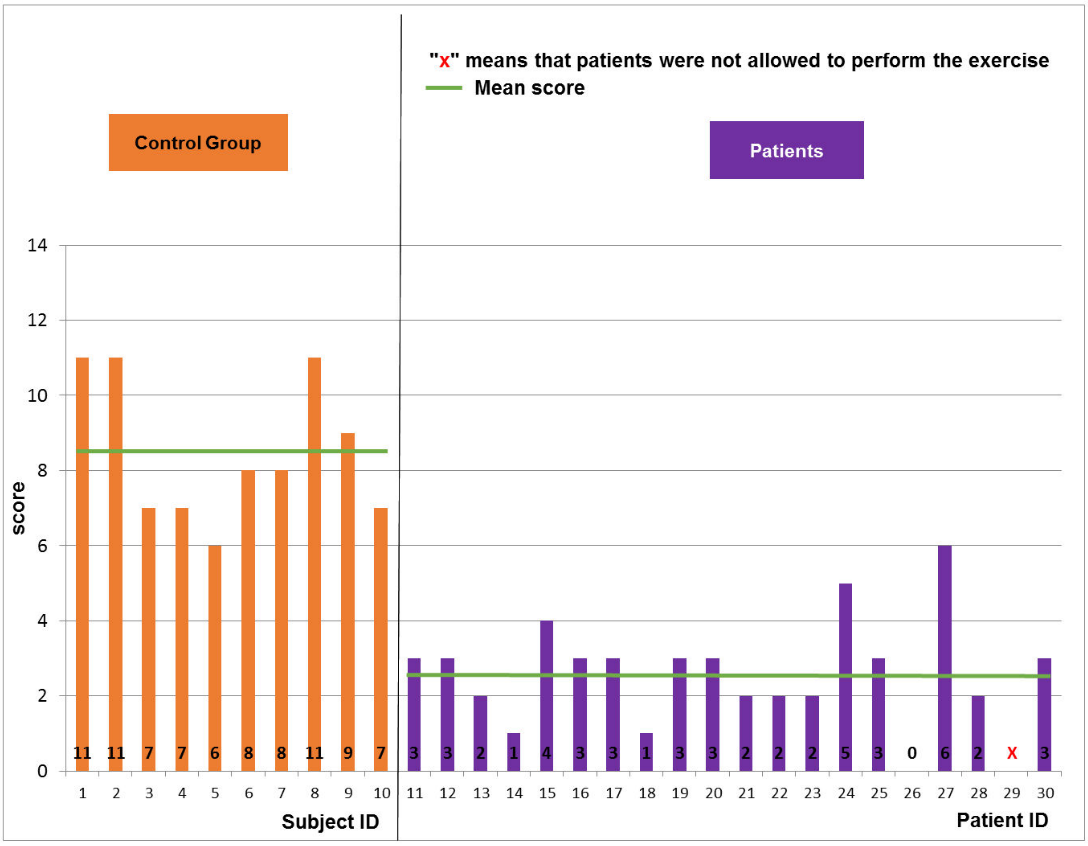


Figure 6. Game performance: patient group vs. healthy control group: medium level of the football scenario.

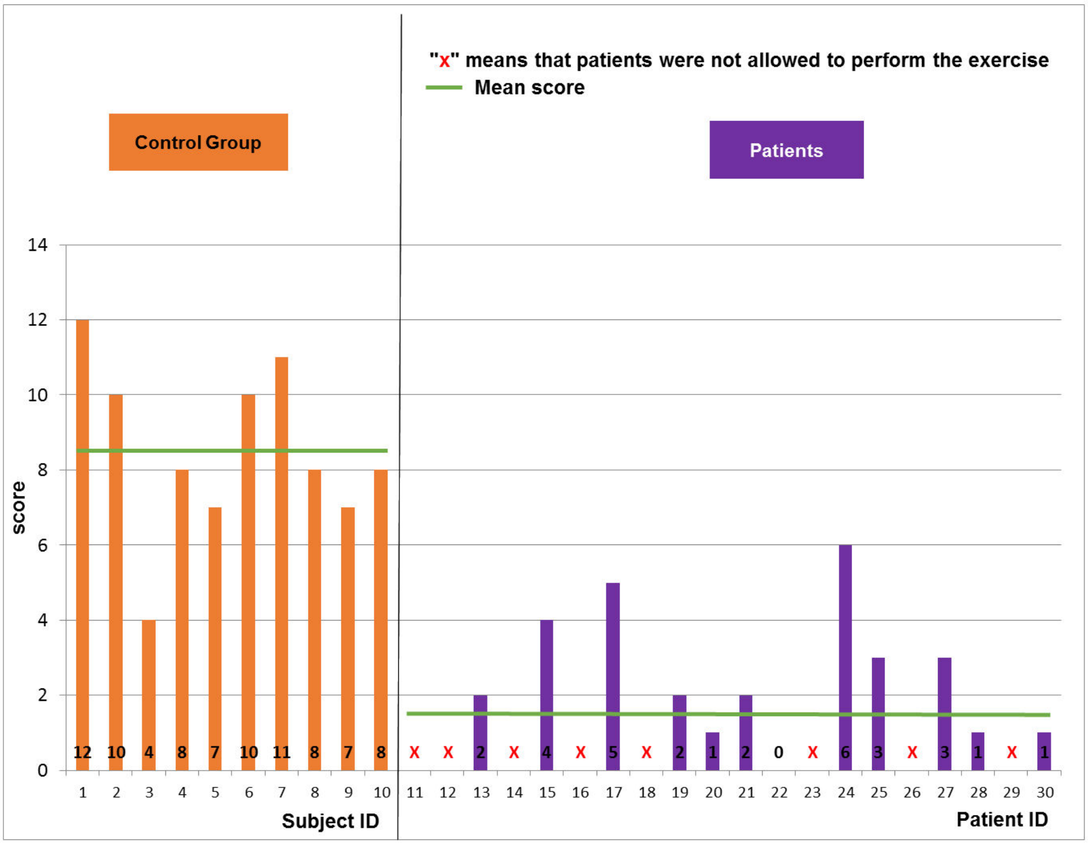


Figure 7. Game performance: patient group vs. healthy control group: hard level of the football scenario.

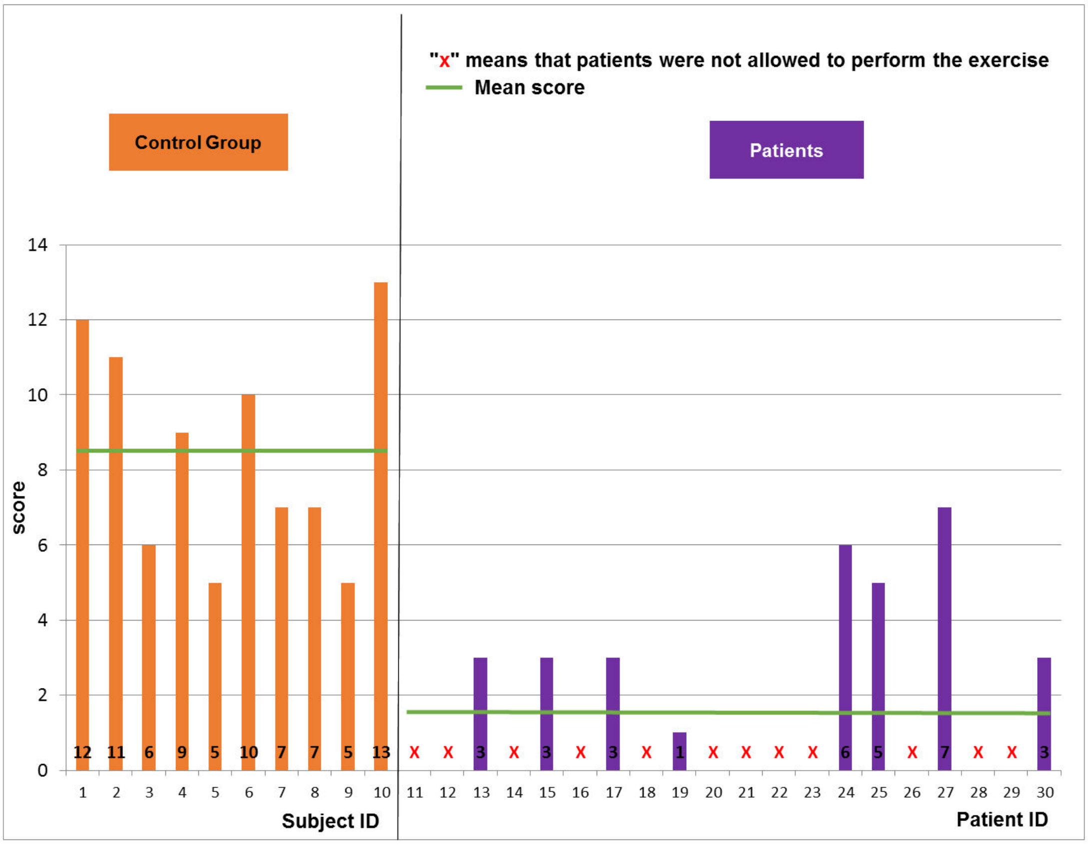


Figure 8. Game performance: patient group vs. healthy control group: easy level of the object manipulation scenario.

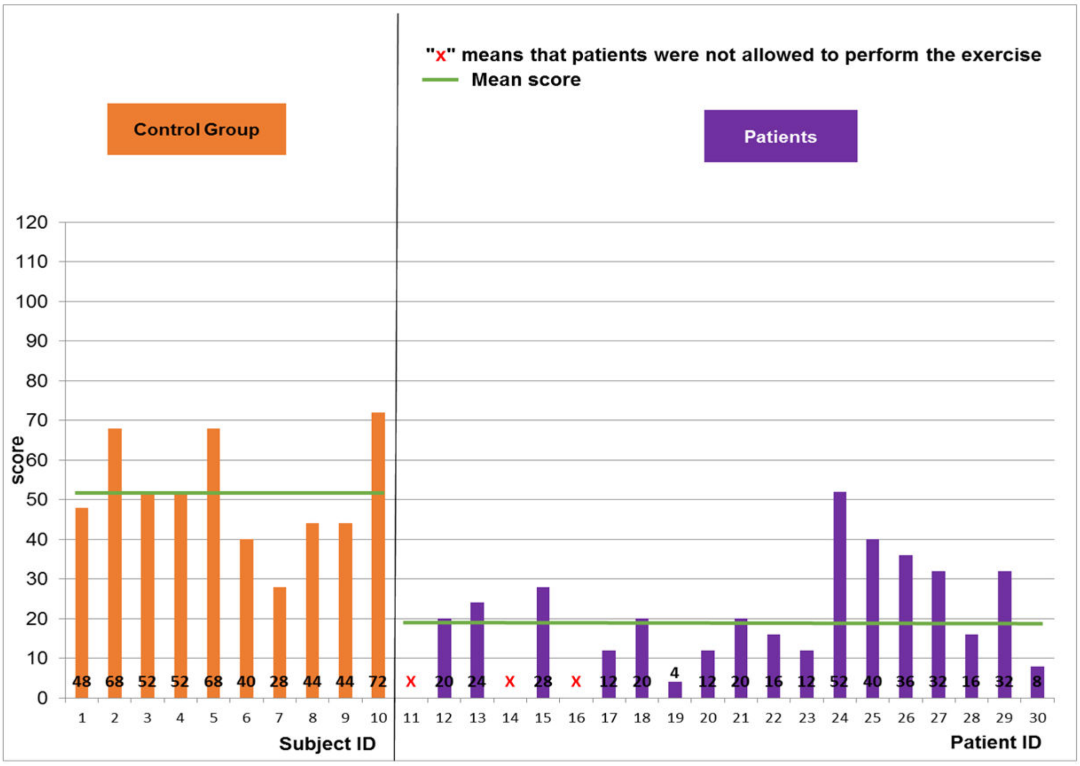


Figure 9. Game performance: patient group vs. healthy control group: medium level of the object manipulation scenario.

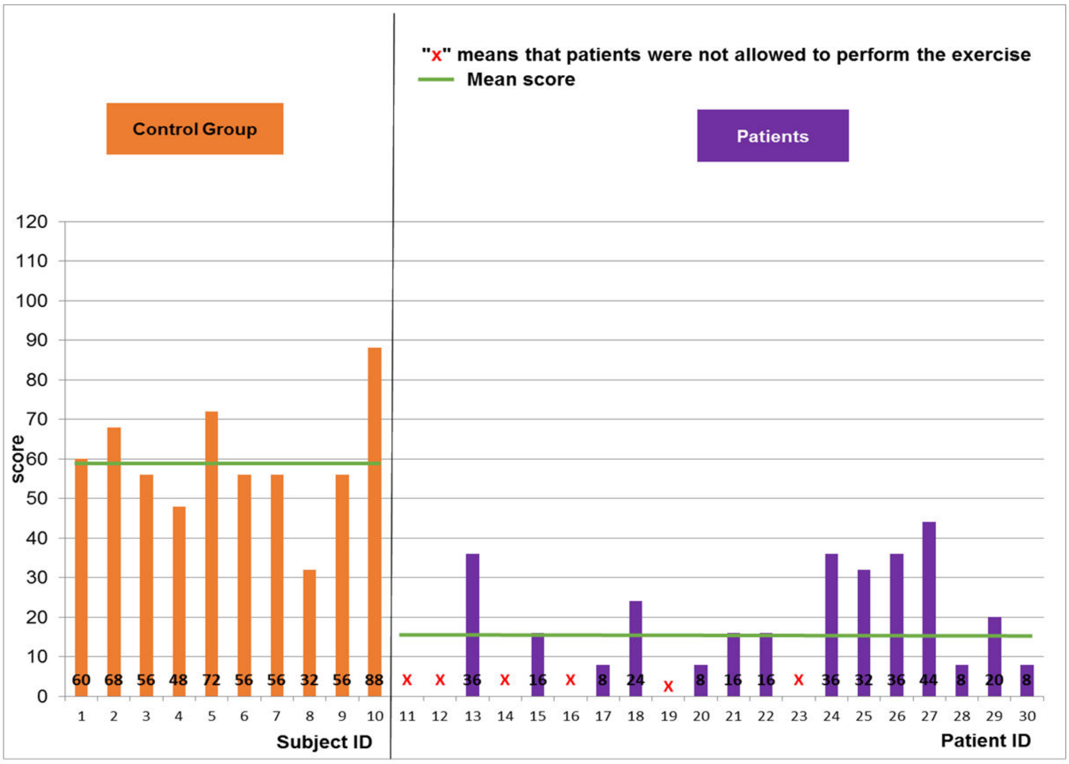
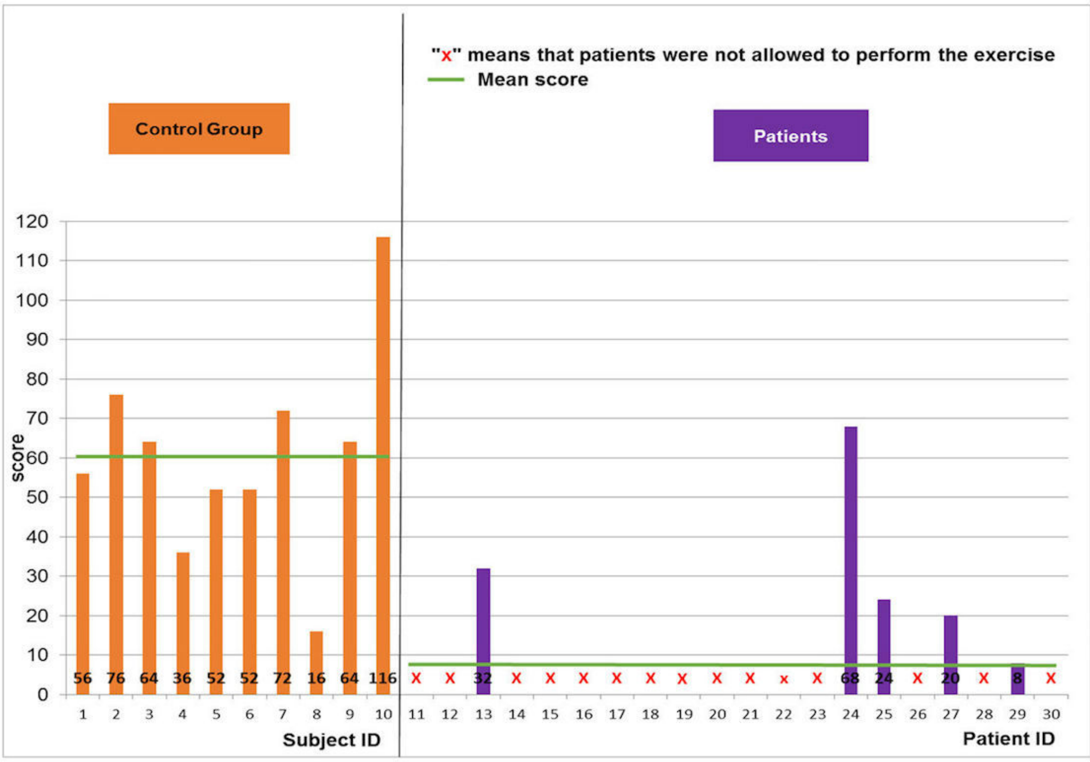


Figure 10. Game performance: patient group vs. healthy control group: hard level of the object manipulation scenario.



Game Improvement

Finally, players were asked to give some specific comments on this project and the developed games. Comments and suggestions from the patient groups are summarized as follows:

> *Interesting game and this game needs to be developed in bigger scales.*

The games are amusing, motivational and not bad at all. It made me really move my legs.

> *The football scene is excellent. I am a football fan and I watch all the games.*
>
> *I recommend you to force the player to hit the left cone at first and then rotate towards the right cone. This improves the efficacy of spine rehabilitation.*
>
> *In my opinion this can really help patients. Even if I am not a florist!*
>
> *The exercises are adapted to rehabilitation at the final stages.*
>
> *The project is suitable for younger players.*
>
> *The project is very fun, helps in performing rehabilitation while enjoying it. It should please young and old people.*
>
> *Very attractive games.*
>
> *Very interesting project for movement coordination.*
>
> *The avatar's movements should be improved.*
>
> *Difficult but interesting. More games need to be developed.*

Based on these suggestions, our game scenarios were updated to take them into consideration. Note that only technical improvement feedbacks were considered in the updated version. In particular, the order of the football game, as suggested in the third comment above, was redefined to adapt to the rehabilitation of spinal patients. Moreover, avatar's movement has been improved by using multi-sensor fusion approach [22]. Some patients did not try the football game because they could not stand up on their feet. This could be an initiative to create exercises for patients sitting on wheelchairs in the future version of our serious game system.

Table 1. Patients' responses to the football game questionnaire.

Criteria	Rank				
	1	2	3	4	5
Game: Objective/goal	1		1	2	15
Unclear (1) → Clear (5)					
Game: Level of difficulty	3	4	7	2	3
Low (1) → High (5)					
Game: Ignorance of achievement			3	2	14
Unawareness (1) → Awareness (5)					
Game: Environment	1		1	5	12
Unattractive (1) → Attractive (5)					
Game: User Interface			3	2	14
Not user-friendly (1) → User-friendly (5)					
Game: Beginning and end	1		1	3	14
Unclear (1) → Clear (5)					
Exercises: Instructions	1			1	17
Unclear (1) → Clear (5)					
Exercises: Variation		3	1	6	9
Low (1) → High (5)					
Exercises: Suitable for game goal		2	5	3	9
Low (1) → High (5)					
Exercises: Feedback		1	3	4	11
Unclear (1) → Clear (5)					
User: Motivating challenge	2	2	1	4	10
Low (1) → High (5)					
User: Mistake permission	6	2	7	1	3
Impossible (1) → Possible (5)					
User: Security feeling			3		16
Uncomfortable (1) → Comfortable (5)					
Total	15	14	36	32	144

Discussion

Principal Findings

Serious gaming technologies target audience ranging from young to adults to the elderly population. The objective of this work was to propose development and evaluation guidelines of serious games for musculoskeletal disorders. The simplicity and challenging aspect are the main advantages of this new technology. Research studies have proposed some interesting solutions over the past decade for the "gamification" approach [23-26]. Seaborn and Fels (2015) reviewed and defined "gamification" as the use of game elements to execute nongame tasks in a game-like environment [27]. In particular, Wattanasoontorn et al (2013) conducted a survey on serious games for health, and they showed that general health was the most targeted by serious games, whereas stroke disease comes in second place [28]. Furthermore, the mouse was the most used interaction tool, mostly used for cognitive rehabilitation. Kinect and Wii Mote cameras tied in first place among motion capture tools. Serious game for functional rehabilitation has become a potential solution to improve the traditional rehabilitation practice [29-32]. Generally speaking, user acceptability was high for some developed games [31]. Clinical improvements over time were also noted [30-32]. However, this new rehabilitation scheme needs to be used with caution because of some negative results. For example, Bower et al (2015) reported minor increases in pain for some participants. Particular attention was also noted for cognitive function and motor impairment patients when using virtual reality rehabilitation games [31]. Thus, the development of rehabilitation games should be done in a well-controlled manner. In previous works, there is no available development guideline for this new rehabilitation scheme. In this study, we proposed a specific task-oriented development guideline to create attractive, motivational, and safe rehabilitation games. The experience that we got from the case study of musculoskeletal disorders showed the usefulness and applicability of the established task-oriented development guideline. Furthermore, an evaluation guideline was also established to propose the common steps toward an objective and quantitative evaluation process. The case study showed the applicability and usefulness of the proposed guidelines in real condition. It is expected that this study may contribute in the definition of customized guidelines for developing and evaluating serious games for musculoskeletal disorders.

Regarding our case study, patients' scores were lower than those of the healthy group. Some of them were not able to play the football scene because of their amputation. Others could not try the object manipulation scene because they cannot move their hands at all. In general, all of them accepted the challenge and wanted to participate in this study. Hemiplegic patients were the top testers among all patients. Medical doctors and physiotherapists thought that these task-oriented games were more adapted to this particular disorder. Previous study came to the same conclusion about the use of the task-oriented games for these patients [16,17]. We can see that all hemiplegic patients were able to try at least one level of difficulty from each game, and their achieved scores depended largely on the severity of their disorder. Amputees tried our system and showed great motivation even though they failed to achieve high scores; they felt the challenge even in the absence of any achievement. Moreover, the Kinect had some difficulty recognizing the shape of their body, which might influence the virtual avatar's behavior. Overall, patients' results depend on the state of each patient. Moreover, even though the difficulty of the games increased, some patients and healthy subjects achieved higher scores even at the hard level of difficulty. This might be explained by the fact that the designed games stimulated the user motivation. Thus, they felt the challenge to perform better when they got familiar with the game. However, more quantitative measurements on user's motivation need to be performed to confirm this finding. Moreover, the increasing scores occurred for the favorite game for each patient. Thus, the choice of the game scenario for the profile of each patient may potentially enhance the achieved scores.

The design of rehabilitation game scenarios plays a crucial role in the success of the serious game for health. The game scenario must not only be attractive but also needs to be clinically useful. In this study, a task-oriented rehabilitation game scenario was proposed. The football and object manipulation games respond to the challenging objective: patient practices rehabilitation exercises without recognizing that it is a rehabilitation exercise when playing the game. Thus, the football game allows the player to practice the two motor tasks (body rotation motion and the leg motion) and two decision-making actions (observation of time and identification of right moment). The object manipulation game allows the player to practice two motor tasks (leg and arm motion) and two decision-making actions (localization of rose or vase, and observation of time). This study suggests that rehabilitation game scenarios should be designed, implemented, and evaluated with similar strategies. The outcome of the case study confirmed the robustness and effectiveness of this strategy.

The design of a motivating, challenging, and safe serious games for functional rehabilitation requires particular attention on the development and evaluation processes. This study proposes useful guidelines to achieve this objective. Thus, the development and evaluation of the 2 developed games (football and object manipulation) followed the proposed guidelines. In general, a guideline is defined as a principle to determine a set of actions in a standard way. This study aimed to propose a coherent set of development and evaluation steps for rehabilitation-oriented serious games for musculoskeletal disorders. It is expected that this proposition may help define a development and evaluation consensus in the health-oriented serious games community. It is important to note that some published works already followed these guidelines [9,10,12] but other works did not conduct some important steps like the improvement of game from user feedback [16] or the evaluation on patients [18]. Thus, this study may serve to highlight the important steps to develop and evaluate a serious game for musculoskeletal disorders.

Our developed system used the Kinect camera as motion capture sensor. Currently, the virtual avatar imitates player movements correctly. However, clinical experts require more precision in analyzing the joint behavior during the exercise. It is well known that the accuracy of this device is limited for joint angle estimation. A deviation range of 11° to 14° was noted for the knee joint motion [8,33]. To overcome this drawback, a fusion process between the Kinect and inertial sensors, placed on the part of the body where experts require more precision, was investigated in another work to achieve a better estimation of joint angles [22]. However, the use of only Kinect camera leads to the feasible and potential translation of such a rehabilitation game into clinical routine practice, especially in a home-based setting thanks to the low cost and portable nature of this specific device. More complex sensors need to be optimized before they are used in a clinical setting. In particular, within the context of a "game," the precision may be sacrificed for the portability and ease-of-use criteria.

Limitations

The main limitation of the 2 developed games is the lack of evident cognitive actions, which could maximize the effect of game outcomes to better manage the functional rehabilitation of musculoskeletal disorders with cognitive impairment [34,35]. Thus, a new rehabilitation game will be investigated to integrate clear cognitive aspects into the game scenario. Thus, cognitive actions may help detect visuo-spatial memory and propose an appropriate rehabilitation program [36]. Moreover, the evaluation of the effectiveness of these serious games will be performed during a long-term campaign to confirm their clinical relevance. Finally, in this study, the user questionnaire was based on the one defined previously [8]. This questionnaire covers many aspects including the game, the exercise, and the user. However, the user engagement aspect is still simple in the used questionnaire. Thus, the use of a validated questionnaire that focuses more on the user aspects to analyze the game engagement will be performed in the future [37].

In summary, this study is an explanatory work aiming to show the usefulness and applicability of the proposed guidelines and associated serious games for functional rehabilitation of musculoskeletal disorders. However, more investigations such as a long-term evaluation campaign for effectiveness analysis and a more quantitative analysis on the user's engagement in the games are needed to fully validate these guidelines [38].

Conclusions

Development and evaluation guidelines dedicated to serious games for health were established in this study. The case study showed the effectiveness and usefulness of these guidelines and associated games. The developed serious game system used the Kinect camera to allow users to interact with two 3D environment scenes (football and object manipulation). Healthy subjects and patients enjoyed the games and found them challenging and amusing. In this work, we concentrated on the assessment data of the developed games. In perspective, the effectiveness and clinical relevance of these games will be studied through a long-term evaluation campaign. And, in the case of positive outcomes, this new rehabilitation game may be translated into clinical routine practice in the near future for the benefit of patients with musculoskeletal disorders.

Acknowledgments

This work was funded within the framework of EBIOMED Chair–IUIS (Institut Universitaire d'Ingénierie en Santé). This work was carried out in the framework of the Labex MS2T, which is funded by the French Government. The authors would like to thank F Chaouche and E Kleinpeter for their useful comments and help on the questionnaire development.

Conflicts of Interest

None declared.

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Abbreviations

3D: three-dimensional
EMG: electromyography
GUI: graphical user interface
ICT: information and communication technology
SD: standard deviation

Edited by A McDougall; submitted 09.01.17; peer-reviewed by T Chang, D Rojas; comments to author 24.02.17; revised version received 28.02.17; accepted 04.04.17; published 04.07.17.

Please cite as:
Idriss M, Tannous H, Istrate D, Perrochon A, Salle JY, Ho Ba Tho MC, Dao TT
Rehabilitation-Oriented Serious Game Development and Evaluation Guidelines for Musculoskeletal Disorders
JMIR Serious Games 2017;5(3):e14
URL: http://games.jmir.org/2017/3/e14/
doi:10.2196/games.7284
PMID:28676468

Original Paper

Designing Serious Computer Games for People With Moderate and Advanced Dementia: Interdisciplinary Theory-Driven Pilot Study

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Abstract

Background: The field of serious games for people with dementia (PwD) is mostly driven by game-design principals typically applied to games created by and for younger individuals. Little has been done developing serious games to help PwD maintain cognition and to support functionality.

Objectives: We aimed to create a theory-based serious game for PwD, with input from a multi-disciplinary team familiar with aging, dementia, and gaming theory, as well as direct input from end users (the iterative process). Targeting enhanced self-efficacy in daily activities, the goal was to generate a game that is acceptable, accessible and engaging for PwD.

Methods: The theory-driven game development was based on the following learning theories: learning in context, errorless learning, building on capacities, and acknowledging biological changes—all with the aim to boost self-efficacy. The iterative participatory process was used for game screen development with input of 34 PwD and 14 healthy community dwelling older adults, aged over 65 years. Development of game screens was informed by the bio-psychological aging related disabilities (ie, motor, visual, and perception) as well as remaining neuropsychological capacities (ie, implicit memory) of PwD. At the conclusion of the iterative development process, a prototype game with 39 screens was used for a pilot study with 24 PwD and 14 healthy community dwelling older adults. The game was played twice weekly for 10 weeks.

Results: Quantitative analysis showed that the average speed of successful screen completion was significantly longer for PwD compared with healthy older adults. Both PwD and controls showed an equivalent linear increase in the speed for task completion with practice by the third session (P<.02). Most important, the rate of improved processing speed with practice was not statistically different between PwD and controls. This may imply that some form of learning occurred for PwD at a nonsignificantly different rate than for controls. Qualitative results indicate that PwD found the game engaging and fun. Healthy older adults found the game too easy. Increase in self-reported self-efficacy was documented with PwD only.

Conclusions: Our study demonstrated that PwD's speed improved with practice at the same rate as healthy older adults. This implies that when tasks are designed to match PwD's abilities, learning ensues. In addition, this pilot study of a serious game, designed for PwD, was accessible, acceptable, and enjoyable for end users. Games designed based on learning theories and input of end users and a multi-disciplinary team familiar with dementia and aging may have the potential of maintaining capacity and improving functionality of PwD. A larger longer study is needed to confirm our findings and evaluate the use of these games in assessing cognitive status and functionality.

(JMIR Serious Games 2017;5(3):e16) doi:10.2196/games.6514

KEYWORDS

serious games; dementia; functionality; learning in context; speed of processing

Introduction

Background

Aging in place is a desirable social and economic goal in our rapidly aging global society [1]. Maintaining cognitive functionality while aging is important to achieve this goal. Cognitive stimulation games have been used and studied as a method for maintaining healthy aging brains [2]. The use of computer games for cognitive stimulation and prevention of cognitive decline in healthy older adults is a fast growing area of research, sometimes referred to as "neuro-games" [3,4].

A budding field of research is the use of computer games for people with dementia [5-9]. With the global rise of people with dementia (PwD) [10] and the huge economic cost of their care, there is an increasing desire to maintain PwD at home and not institutions, for as long as possible [11]. One of the key factors in keeping PwD in their homes, as opposed to nursing homes, is related to their ability to maintain functionality of simple daily activities, despite their cognitive decline. Indeed, when families opt for institutionalization, it is usually on the basis of a loss of the PwD's ability to eat independently, as well as perform activities related to personal hygiene, such as grooming and toileting [12]. The development of modalities to maintain aging in place for PwD could include computer-based games specifically designed to accommodate functional limitations and build on their remaining capacities [13-15].

Serious games offer the promise of low cost interventions in the care of PwD [16]. In addition, they require minimal professional supervision (ie, by an occupational therapist) and can be played with the assistance of formal or informal caregivers. The American Society of Occupational Therapy has developed computer applications for assisting individuals with autism and dementia [17]. However, very few of the efforts cited have used theory-driven learning theories in the game development or reported on the iterative human centered design process of game development with the end users involvement.

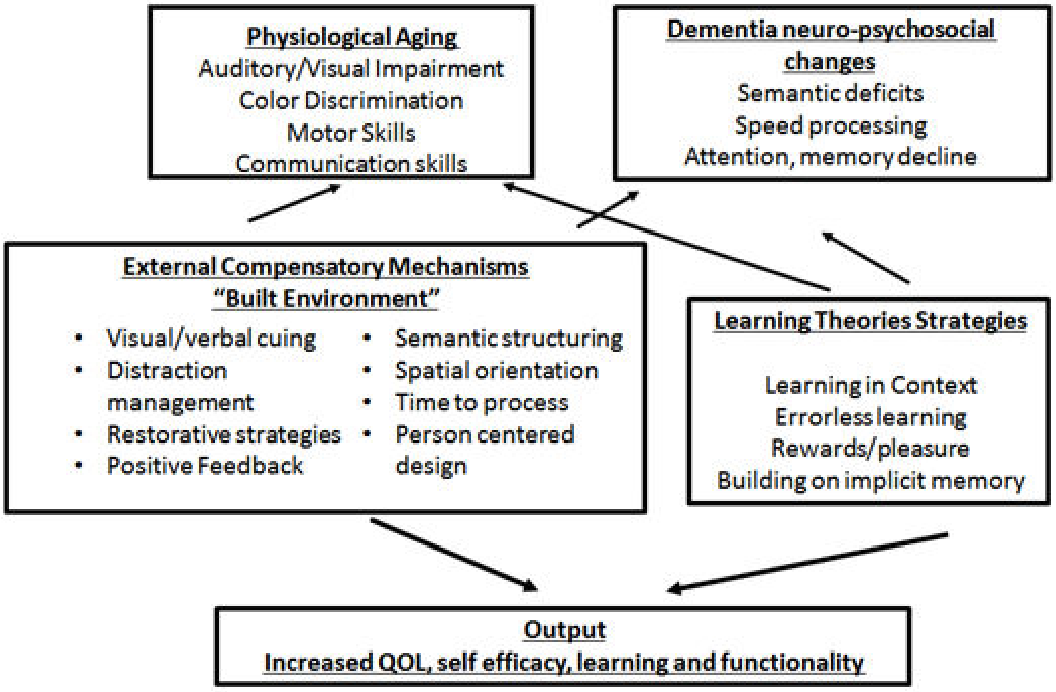
This paper aimed to contribute to methodology of game design for PwD. Our goal was to create a serious game that is acceptable, accessible, and engaging for people with moderate and advanced dementia based on DSM-5 criteria [18]. Our approach aims to bridge the transfer gap between "game designers" practice and knowledge, and neuro-psychosocial scientific knowledge of aging and dementia. In addition, our game design considers theories of learning and the impact of the "built environment" as compensatory constructs in learning. The overall aim of our gaming approach was to facilitate people with moderate and advanced dementia to arrive at an increased sense of self efficacy, which, according to recent research in neuropsychology, directly contributes to psychological, cognitive, and physical health, and thus serves as a key enabler in exercising and prolonging functionality [19].

Theoretical Framework for Game Screen Development

The game was designed with input from a multi-disciplinary team familiar with aging and dementia and gaming theory as well as direct input from end users (the iterative process) [20]. Each game screen was developed with the input of 34 PwD, 14 community dwelling healthy older adults (ages 65-90), an occupational therapist, gerontologist, an MD PhD specialist in technology for health, a computer engineer, and a PhD cognitive psychologist specializing in cognitive and sensory aging. The complete game includes 39 screens.

The theoretical models that form the underpinnings of our game are based on a multidisciplinary model outlined in Figure 1. The key frameworks involved (1) acknowledging the physiological changes associated with aging, (2) dementia's neuropsychosocial induced changes, (3) applying learning theories that focus on "errorless learning," learning in context, and building on remaining capacity (implicit memory), (4) external compensatory mechanisms, the "built environment" theoretical constructs including design, spatial orientation frames all brought to bear on, and (5) improving "self-perceived" self-efficacy. In later sections, each of these topics is briefly discussed first, and then the person-centered technological approach to the game development is presented, followed by the description of the iterative process of developing the game screens with direct input from the end users (people with moderate and advanced dementia).

Figure 1. Multidisciplinary constructs and theories in designing serious games for people with dementia.



Enhancing Self Efficacy in PwD

The most important construct influencing our gaming strategy is aimed to enhance the self-efficacy of PwD, an important component of executive function [21]. A central problem that PwD experience is the gradual loss of cognitive and physiological capabilities in their daily lives. Indeed, not just intellectual tasks but simple activities of daily living (ADL) become more challenging. However, the literature shows (and experiential data in our daycare centers supports) there is a gap between a PwD capacity to learn and participate in daily tasks and their performance, as measured by cognitive instruments [22]. Physiological decline impacts on the PwD's speed of completing tasks and movement. This is often exacerbated by family and caregivers who significantly and unknowingly contribute to PwD's choice-limitations, as related to everyday living activities. Caregivers tend to do things for the PwD that the PwD could do on their own. This excessive involvement and over protection by caregivers tends to reduce the PwD's confidence in their own abilities and competence, leading to premature disengagement by the PwD. On the other hand, adapted environments encourage independence in activity and help to maintain one's sense of perceived self-efficacy [23].

The concept of self-efficacy has grown out of a social psychology construct of human agency [24]. However, its bases are very old and embedded in such perennial philosophical underpinnings as theories of determinism, choice, intentionality, free will, and causality. There are 2 distinct, yet overlapping, theories that underlie the self-efficacy: (1) Motivational theories, which conceptualize self-efficacy in motivational terms and (2) Cognitive theories, which conceptualize self-efficacy in terms of expectancies and perceptions of control. Both theories, alongside empirical evidence, support the notion that self-efficacy plays a significant role in functionality (physical and cognitive) of PwD [25]. Therefore, our highest level objective in our design strategy was to utilize serious games to create the conditions and opportunities to rebuild and maintain a sense of self-efficacy, along with acknowledging the challenges on self-efficacy arising from normal and pathological physiological changes, as well as the PwD's family and caregivers attitudes toward this slope of decline.

Cognitive Changes Related to Aging and Dementia

One of the main characteristics of dementia relates to cognitive impairments, specifically, changes in memory encoding and memory retrieval. In addition, research supports that PwD also experience a reduction in executive functions—including planning, working memory, and selective attention [26]. Executive functions are central to most cognitive processes: the ability to focus on one aspect of the environment, to ignore other unrelated information, and to switch between them when prompted.

Selective attention has been marked as one of the major areas of cognitive impairments in dementia in general and Alzheimer dementia specifically [27], related to a reduction in the efficiency of inhibition [28], above and beyond age-related changes. This impairment may be linked with changes to frontal lobe regions [29]. These cognitive changes should be considered during game development. For example, reduced efficiency of inhibitory processes may translate to difficulties PwD will have in ignoring the irrelevant information presented on the screen during the game, or the information embedded in an irrelevant dimension of the stimuli presented (for a further discussion see Lustig et al [30]). Several aspects of our game were designed to tackle this change. For example, our design strategy was to avoid the clutter of the screen, thus reducing the amount of information PwD will need to inhibit. Additional factors related to the dementia process were taken into consideration, such as attention span, inhibition of initiation or perseveration, eye hand coordination, semantic sequencing, orientation to time and place, sustained attention, agnosia, and judgment.

Sensory Motor Degradation Related to Aging and Dementia

Research shows that PwD do not face only cognitive deficiencies related to executive function, but also other deficiencies in auditory [31,32], visual [33] and other sensory systems [34] that contribute to cognitive deficits and difficulties in daily functionality [35]. For example, Ben-David and colleagues [36] have recently showed that reduced performance for PwD (as compared to healthy older adults) on a task that gauges executive functions (the Stroop color-word test) can be partially mediated by dementia-related changes in color-vision [37]. Auditory changes can also lead to reduced cognitive performance, especially in daily life activities such as communication [38]. This dual sensory loss (visual and auditory) also has direct implications on game administration. It reduces the comprehension of spoken instructions and increases the effort and the amount of cognitive resources invested in speech processing, thus tapping into the already reduced pool of resources [39-41]. Together, this cognitive and sensory interaction is expressed as a part of the information degradation hypothesis [42]. The theory postulates that as the perceptual system receives degraded information from the senses, it leads to reduced cognitive performance.

To address the above listed challenges, we considered multisensory approaches to enhance PwD's daily functionality, such as using a variety of cues [43], both visual and auditory [44], as well as adjusting color and light setting. For example, an estimate of 88% of the aging population have very high failure rates of discrimination in the red-green and blue-yellow spectrum [45]. These age-related physiological changes were taken into consideration during the design relating to layout, color and instruction delivery methods and demonstration. Special attention in the design of the game was paid to the linguistics/semantic challenges of PwD [46-48].

Finally, sensory-motor degradation was considered in the design of the game environment. For example, during the iterative process, we learned from the comments of the end-users (34 PwD and 14 healthy community dwelling older adults) and the observations of the testers that the placement of the tablet has to be such as to allow visualization with natural light and no screen glare from artificial light or sun. The tablet should be placed in a comfortable position for the PwD, table height, and in a quiet environment with few distractions (again acknowledging cognitive changes).

Making the Game Engaging

Serious games for older adults should be engaging and fun and further contribute to easing the personal burden of families and caregivers of PwD, as Robert and colleagues [49] among others, point out. The motivation to perform the task, an often-ignored factor, plays a large role in the performance of older adults. Specifically, framing tasks in an engaging, relevant context can improve performance [50]. For example, research by Zimerman et al [51] suggests that cognitive tasks, targeted originally with college students in mind, appear unsnagging for older adults, and may impact negatively on their ability to perform at their full capacity. This is of specific importance, as PwD are much more focused on emotional and social issues than on abstract problems [52-54]. While we aimed to design the serious game application in a simple "clean" fashion to facilitate sensory and cognitive processing, we were aware of the importance of designing the game screens in a visually engaging way. We postulate that when performing a task in an engaging context and by choosing stimuli that relate to PwD, the resulting increase in perceived self-efficacy would increase executive function and thus improve learning and performance. These relevant learning theories are discussed next.

Learning Theories

The majority of serious games, or games for health, have utilized the important construct of entertainment as the major motivator for game construction. In our efforts to create a game for PwD based on information and communication technology (ICT), we put emphasis on age appropriate entertainment venues as defined by the end users themselves, and based on the concept that fun "learning in context" is a framework that induces capacity building for all persons and especially those people with disabilities, both physical and cognitive [55].

Learning in Context

"Learning in context" has been defined in a variety of ways, however, the basic supposition is that adult learning does not take place in a vacuum, but within a sociocultural model, or as Hassin coined: learning "outside the mind" [56]. In the sociocultural models, learning is not something that happens, or is just inside the head, but instead, it is shaped by the context, culture, and tools in the learning situation. Russian psychologist LS Vygotsky was the pioneer of "learning in context", a sociocultural theory of learning, in contrast to psychological and behavioral understandings of learning [57]. His work is based on the concept that all human activities take place in a cultural context with many levels of interactions, shared beliefs, values, knowledge, skills, structured relationships, and symbol systems [58]. These interactions and activities are mediated through the use of tools, either technical (machines, computers, calculators) or psychological (language, counting, writing, and strategies for learning), provided by the culture [59]. These tools ensure that linguistically created meanings have shared social meanings. His theories are relevant for our end-users, PwD, using technical and psychological tools to build upon the cultural learning of PwD and practice skills. Thus "learning in context" is a form of situated cognition [60]—that is, learning is inherently social in nature. Following this approach, learning takes place in 5 sequential phases that allow scaffolding of learning experiences (for a review, see [61]): (1) modeling, (2) approximating, (3) fading, (4) self-directed learning and, (5) generalizing.

Learning in context has been linked with basic cognitive constructs. Nisbett [62] postulated that implicit memory and learning is one of the products of context learning, based on the ontological assumption that interpretations of tasks are based on a background of past experience and intellectual resources. Nisbett suggested that cognitive structures are constructed and developed in particular social circumstances. The significance of cognitive structures resides in their deployment in cognitive activity, such as problem-solving, transfer, and learning.

Given the cognitive, physical, and sensory challenges of aging people with dementia, we focused on the above cited literature on learning theories to support our use of game screens, based on contextual learning. Specifically, our game screens utilized cultural memories and implicit memory, which are relatively more preserved for PwD. Implicit memory is one of the two main types of long-term memory which has recently been actively investigated as an important construct of cognitive function and overlooked to the usually measured explicit memory. Implicit memory includes procedural learning (eg, skills and habits), priming, and classical conditioning. These learning processes do not require conscious recollection of information, instead learning is expressed through performance or behavior [63]. Indeed, implicit memory or specifically non-declarative memory is acquired and used without the need (or ability) to verbally describe the process. For example, in procedural memory when tying one's shoe or riding a bike, processes are learned and conducted without consciously thinking about the actions. It is a type of indirect, unintentional manifestation of prior experience [64].

Explicit memory, on the other hand, refers to the conscious, intentional recollection of factual information, previous experiences and concepts. While the literature documents well an age-related decline in explicit memory, numerous studies have shown that implicit memory is spared in older adults [65-67]. Even mild cognitively impaired older adults [68] and people with Alzheimer disease [69] showed some form of preserved implicit memory. This capacity can be utilized for reinforcing scaffolding learning theories. The aim of our game is to focus on practical activities in an entertaining, visually captivating and age appropriate presentation based on scaffolding learning theories [70].

Errorless Learning

Within the framework of situated cognition learning in context, errorless learning methodology and cueing offers an important path to present the task so that a PwD overcomes inhibitions and limitations arising from low perceived self-efficacy. Errorless learning is "a teaching technique whereby people are prevented, as far as possible, from making mistakes while they are learning a new skill or acquiring new information" [71]. Major ways of achieving errorless learning are to use various cues, to complete the task collaboratively with the PwD, adjust the expectations of both client and designer, and make the task as doable as possible to the PwD. This approach assumes that new learning is stronger and more durable if mistakes are eliminated during training. Performance becomes automated through imitative learning and repetitive practice of perfect task execution. Errorless learning is not suited for all populations. With neurologically intact individuals, conscious or explicit memory of having made an error minimizes the impact of error learning. However, the deficit in explicit recall in PwD eliminates this counterweight to error learning and renders a PwD more vulnerable to its negative impact. In other words, PwD may remember the error, rather than learn the correct way to complete the task (ie, rather than learning that it was an error).

In the pertinent literature, there is an ongoing debate about the benefits of erroneous [72,73] versus errorless learning on memory creation. However, incorporating errorless learning scenarios within an active learning paradigm is a widely accepted practice in rehabilitation and dementia treatment, as it was found to maximize successful retrieval opportunities [74,75]. Indeed, errorless learning is taken as an encoding method that results in superior retrospective memory compared with erroneous learning. Neuropsychological studies indicate that people with compromised explicit memory are adversely affected by errors made during learning, and that implicit memory is sufficient to produce an errorless learning advantage for PwD [76]. This is perhaps due to the fact that erroneous learning demands greater frontal/executive contributions [77].

It is important to highlight the fact that there is something lost in an "errorless learning" approach. Psychological research in learning and memory identifies the opportunity to engage in difficult (hence error-prone) as very important in successful learning, most specifically for retrieval of learnt information (for a review, see [78]). However, working with PwD, we aim at compensatory learning approaches in an attempt to improve function by recruiting relatively intact neurocognitive processes to fill the role of impaired ones. Thus, it is assumed that new learning is stronger and more durable if mistakes are eliminated during training. Performance becomes automated through imitative learning and repetitive practice of perfect task execution [79].

In summary, all other factors being equal, it appears that there is ample evidence to suggest that errorless learning procedures are likely to improve retrieval in people with memory impairments relative to erroneous methods [80].

Cueing, Priming, and Semantic Considerations

In addition to errorless learning in PwD, the procedure of cueing or priming and semantic structuring of instructions are important elements in cognitive functioning especially in semantic dementia. Priming is an implicit memory effect in which exposure to one stimulus (ie, perceptual pattern) influences the response to another stimulus [81]. The literature generally suggests that performance on implicit memory tasks, such as repetition priming, deteriorates in AD. However, these AD-related impairments were not found for all priming tasks. Indeed, in a longitudinal study using different priming tasks, only conceptual priming task (category- exemplar) was significantly impacted by AD neuropathology. Priming tasks that involves perceptual processing (word-identification, picture-naming, or word-stem completion tests) were not necessarily associated with a decline in AD [82,83]

Consequently, we chose in our game the use of visual-spatial cueing or priming [84]. Visual-spatial cueing represents a form of learning in context [85,86]. Using context to facilitate object recognition has gained importance in design, acknowledging both the role context plays in object recognition in human visual processing (Gestalt theory) and the striking algorithmic improvements that "visual context" has provided [87]. Based on the learning theories presented, we opted to use encouraging prompts when an error occurred. This method minimizes erroneous learning. Thus, it increases the impact of self-efficacy, building on the remaining capacities of a person to learn how to play the game successfully.

Special attention in the design of the game was given to the linguistics and semantic challenges of PwD, (for example, see [88,89]). These principles were incorporated in our game design by structuring the instructions in short simple sentences, for example, "Please drag the ball to the boy." The modality of instructions delivery was also considered, in view of limitations in sustained attention, possible visual and auditory degradation, and cultural nuances of language. Therefore, in our game, instructions are provided in writing for each game screen, as well as vocal spoken instructions adapted to the culture of our target population. Every instruction for each game screen was tested with the end-users, (34 PwD and 14 healthy community dwelling older adults) various times during the iterative development process. Game screens were adapted and corrected for the final prototype game based on the verbal feedback of the end-users, as well as their ability to understand the instructions and succeed at the game as observed by the testers.

Interaction of the Different Elements and Built Environment

We adopted modern viewpoints on cognitive performance in aging that consider the full context rather than focus on performance alone. In these views, all the elements of the model interact to shape performance. This complex interplay guides us in our design of the game and in our focus on human-centered technology, as discussed in the next section. For example, sensory changes were noted to affect performance on cognitive tasks in older age (sensory degradation hypothesis [90]), where reduced performance was linked with reduced acuity. Game engagement will clearly also be affected by sensory changes, as reduced sensory input leads to more effortful processing, potentially reducing engagement [91]. In other words, the game is less engaging if one cannot see it clearly. Learning in context is chosen to overcome cognitive changes in dementia, by using the most preserved intellectual abilities and knowledge [92]. Similarly, the choice of cueing and priming is designed considering visual sensory changes, and cognitive changes in dementia. Likewise, instructions and their presentation were designed considering learning in context, along with cognitive [93] and sensory changes.

This interplay can be exemplified in the variety of elements that are best classified as "built environment." Built environment encompasses the design parameters related to the technological (machine) and screen design characteristics, as well as the physical environment within which the prototype game was pilot tested. In describing their CREATE model on designing technology for older adults, Rogers and Fink [94] explain that successful performance depends on demands imposed by the environment relative to capabilities of the individual (environmental press). This model illustrates the range and type of variables that must be considered when developing technology for older adults. As described in this introduction, our design methodology has taken many variables into consideration in order to develop a game best suited to PwD.

Technology Considerations

In our overall strategy, we focused on person-centered technology, including the following 2 central guidelines: the Human Centered Design (HCD) and the Iterative Process [95,96].

The definition is outlined in the International Standardization Organization (ISO) standard Human Centered Design for Interactive Systems: ISO 9241-210 [97]. The HCD ISO guidelines are as follows: (1) Understand and specify the context of use, (2) Specify the user requirements, (3) Produce design solutions, and (4) Evaluate. We embedded this process within the iterative design process, where end-users (34 PwD and 14 healthy community dwelling elders) were involved directly in the creation and clarification of each game screen. The iterative, human centered approach [96] is the strategy we chose to follow for development of each game screen, as research shows that PwD, despite cognitive decline, can (and should) provide insight and user feedback that improves usability and human experience [98].

For example, at first we planned to use laptops, because we thought the portability would be convenient and the screen size would be appropriate for older adults. However, during the iterative development process, we learned from the end-users and observations of the testers that tablets were preferable, therefor the game development was switched from laptops to tablets. Tablets are easily mobile and can be easily disassociated from the keypad—a technology that often appears intimidating to PwD. Moreover, tablets use a touch screen and/or a stylus, an object resembling a pen, an element likely to be culturally more familiar to PwD then a keyboard. As we live in a society where technology is ubiquitous, our theoretical presupposition is that self-efficacy of PwD would be enhanced by their successful use of tablet technology [99,100].

Game Framing Methodology

Broadly speaking, we developed a matrix based on the aforementioned theoretical frameworks that guided the creation of every game screen. A brief summary of these variables is depicted in Table 1. The aim was to create a fun and engaging game environment that is, on one hand challenging enough to provide an exercising and learning effect, while on the other hand, specifically adapted to assist in exercising key cognitive strengths a PwD has available (such as implicit memory), while providing assistive mechanisms to help overcome extraneous limitations (that would impede the accomplishing of tasks).

Table 1. Examples of variables taken into consideration for game screen frames.

Challenges	Variables	Solutions
Sensory degradation	Visual	Avoid blue or yellow combination, script choice
	Spatial placement of fields of action	Center of screen
Learning	"Learning in context" visual elements	Culturally relevant
	Cuing	Placing correct answer center screen, reminder by reading instructions over
	Feedback	Positively framed, immediate, errorless, and entertaining
Cognitive changes	Semantics	Simple action oriented instruction
	Uncluttered (inhibition)	No unnecessary information
	Technology complexity	Each time the game is played, it is preceded by practice exercises related to tablet use (ie, touch and drag functions). The practice exercises aren't included in the analytics of the game session

We identified a set of functional simple daily tasks that are essential and culturally relevant to daily life. Each task was then divided into subtasks, utilizing an occupational therapy methodology, primarily adapted from neuro-rehabilitation [101]. Each subtask was further clarified in terms of the main key cognitive skills it reflects. While it is of course not possible to untangle different cognitive skills during task performance, it is possible to identify the main cognitive skills around which the game screen is designed, that is, executive function, eye hand coordination, working memory, and prolonged attention [102].

Each game screen was person-centered [103], and was designed in such a way that a measurement instrument collected game performance data (ie, speed of initial interaction with the game screen, speed of successful screen completion, and number of screens completed successfully).

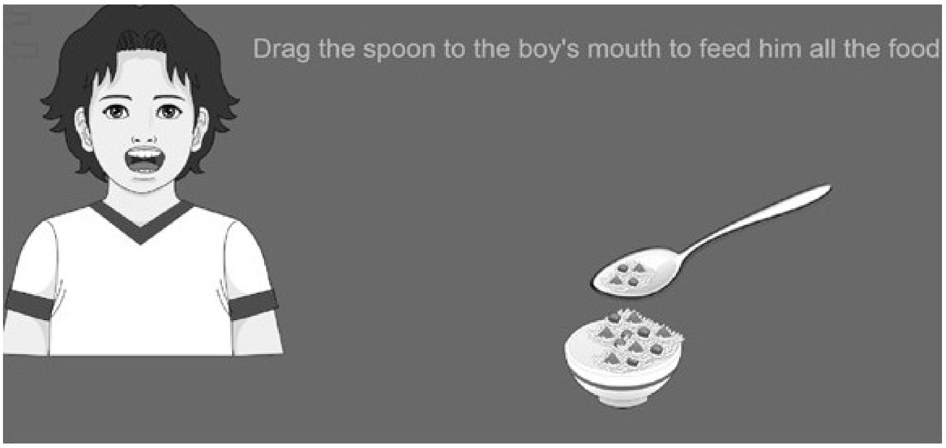
One sample game frame is presented in Figure 2. In this frame, the PwD was instructed to follow written and oral instructions to find, drag, and move items on the tablet touch screen. Table 2 describes the other various actions or tasks the PwD were asked to do in other game screens. It also lists the skills targeted by all of the game screens.

At the end of the iterative development stage, we had developed a prototype of a tablet-based game for PwD with 39 game screens. The prototype was used for the proof of concept pilot study that we report on next.

Table 2. Game screens: game types and skills involved. A list of the nine major game types used in the study, with all relevant physical and cognitive skills targeted.

Game types	Physical, cognitive skills targeted	Skills targeted on all games
1. Identify, find and touch	Gnosis	Eye hand coordination, language skills (reading, comprehension), understanding and following instructions, praxis, memory, sustained attention, and object recognition.
2. Identify, find and drag	Association, gnosis	
3. Identify, find, touch alternating correct answers	Mental rigidity	
4. Find, sort and drag	Gnosis	
5. Time orientation	Recognition, abstraction, association, match activity with time of day	
6. Space orientation	Recognition, gnosis	
7. Hold release action	Inhibition, basic math skills	
8. Drag things on screen into a sequence	Logic, executive functions	
9. Language exercises	Word finding, letter recognition, gnosis, semantic sequencing	

Figure 2. Sample game frame.



Goals

The aim of our research was to answer the following questions: (1) Are serious computer games acceptable accessible and engaging for people with moderate and advanced dementia? (2) Are people with moderate and advanced dementia able to use a tablet? and (3) Can PwD improve the speed of performing a task with practice, indicating their ability to learn?

Methods

Procedure

A pilot study for proof of concept was conducted to answer the above questions. The game was played with the PwD and a tester present in a quiet room, located in the MELABEV dementia day center, Jerusalem, Israel. MELABEV has four day-care centers attended by approximately 500 PwDs, ranging from people with moderate cognitive impairment (MCI) to advanced dementia. MELABEV's professional staff routinely uses computer games on a one-to-one basis for cognitive stimulation gaming [104], as well as reminiscence therapy at the computer [105]. Primary family caregivers who enroll the PwD in the day care program consent to the participation of their family member with these kinds of technology, as well as all other activities in the day care center.

Meaningful informed consent for people with dementia is challenging. Thus, for our pilot study, we utilized the participatory consent process [106]—each time a game was presented, the participant was asked by the tester if she agreed to participate in the gaming session. Upon agreement, the PwD voluntarily got up and was guided to the designated space the computer room, to play the game. If the PwD did not agree to participate, he/she remained in the regular activity room, did not go to the computer room and did not use the game that time, with no consequences what so ever to the services they received in the center. If at any time during the game session, the PwD said or acted as if they didn't want to continue, the game session was terminated and they were taken back to the regular activity room.

During the 10 week pilot study, the PwD played the prototype game 1-2 times a week under supervision of testers. There were 6 different testers. All testers had past experience working with the PwD population: occupational therapist, gerontologist, social worker, pre-med student, occupational therapist student, and activity worker. Only 2 of the 6 were involved in the development of the game.

Testers' main task was to observe the sessions and manually record their observations related to the PwD's interaction with the game for each game frame. They also recorded unsolicited, unprompted spontaneous verbal comments made by the PwD while using the game. Also, testers assisted PwD to maintain their attention on the game throughout the session by prompting them to refocus, when this was called for. Finally, testers were instructed to assist with any technological issues that might arrive.

Each game session was between 20-30 minutes, a recommended time for therapy sessions with PwD. All sessions took place at approximately the same time of day in a quiet room. In every game session, each PwD had the opportunity to play the complete game of 39 game screens. Each game screen was played in the following way. If they were successful, they received a success message (audibly and visually) relevant to the activity performed. If the PwD did not succeed at first, they were cued (audibly and visually). The cueing procedure repeated 3 times, and then, even if the person didn't complete the screen successfully, the game advanced to the next screen. Success or failure, as well as other variables were recorded internally by the tablet.

Participants

Out of about 200 PwD from two of MELABEV's day care centers with moderate to advanced dementia, 24 persons were found to fit the inclusion criteria and participated in the pilot study (age range: 65 years – 90 years, 15 women, and 9 men). The PwD included had cognitive assessment scores (as tested by the Montreal Cognitive Assessment MoCA) as low as 6/30 [107] or a Mini-Mental State Examination (MMSE) as low as 10/30 [108]. We excluded patients with aggression, delusional behavior, a history of alcohol or substance abuse, depression, severe auditory, and visual or motor deficits, as assessed by the professional staff at MELABEV.

Fourteen healthy community dwelling older adults (age range: 65 years – 90 years; 11 women, 3 men) also volunteered to participate in this process. Game sessions took place in their homes at the time that was convenient for them. These older adults served as an age-matched control group and could verbalize their opinions relating to the games accessibility and acceptability better than PwD.

Analysis

A mixed methods approach was utilized for evaluation [109]. Quantitative data for each participant was recorded automatically by the tablet platform, collecting game performance data on speed of successful screen completion and task completion rate. These data were analyzed using a mixed-model repeated-measure ANOVA (analysis of variance).

Qualitative data included the observations of the 6 testers from each game session they participated in, as well as the spontaneous comments from participants during the game session. The testers recorded their observations and the participant's comments relating to each game screen in an Excel document immediately after each game session. The Excel (Microsoft) document was analyzed for themes using grounded theory by 2 researchers and a research assistant, each one separately. Analysis was then discussed as a group between the 3 researchers until consensus about common themes was reached. A list of 10 themes emerged. One of the major themes relates to self-efficacy of PwD and is discussed in this paper. Other themes will be discussed in a future paper.

Results

Participants

Of the 24 PwD who began the pilot study, 12 (50%) dropped out during the study. Reasons for dropping out included: rapid deterioration of physical and/or cognitive condition, vision deterioration, did not attend day care center due to illness, institutionalization, death, preference of other programs going on in the activity room, lack of interest in the game, and found the game to be too easy. Of those that dropped out 3 (12.5%) were game related (too easy, didn't interest them) and 9 (37.5%) were aging or dementia related.

Analysis

As expected, quantitative analysis showed that the average speed of successful screen completion was significantly longer for PwD compared with healthy older adults, t_{34}=4.4, P<.001 (see Figure 3), with an average of 45.5 (SE 5.1) and 17.4 (SE 1.1) seconds/game frame for PwD and healthy controls, respectively. Note that, as expected, performance was much more varied across PwD than across controls.

Next, Figure 4 presents the average speed for successful screen completion for the first 3 sessions, separately for PwD and controls. To test whether performance improved with practice to the same extent for the two groups, a mixed-model repeated-measures ANOVA was conducted. Speed of screen completion was the dependent variable, session (1, 2, or 3) served as the within participants variable and group (PwD vs controls) as the between participant variable. A significant linear trend for session (ie, session 1 > 2 > 3) was found across both groups, $F_{1, 20}$=6.1, P=.02, η_p^2=.23, denoting an increase in speed with practice. Clearly, a main effect for group membership was noted, with significantly slower performance for PwD than for controls, $F_{1, 20}$=23.3, P<.001, η_p^2 = .54, but the linear trend did not interact significantly with group membership, $F_{1,20}$=1.1, P>.3. In other words, the rate of improved speed with practice for PwD and healthy controls was not statistically different. Finally, the average number of game screens completed correctly by PwD per game session was 13.4 out of 22, representing 61% of the game frames.

In sum, these results may suggest that the tasks were well designed for the PwD group that is challenging enough to encourage improved performance, but not too challenging as to frustrate learning. For our control group, it appears that the tasks were easy and they quickly reached a ceiling of performance. Most importantly, it appears that when tasks are designed with PwD in mind, the rate of improvement in performance with practice (ie, learning) is not significantly different than the rate for healthy age-matched controls.

Qualitative analysis of the PwD spontaneous comments (eg, expressed while playing the game), as recorded manually by testers, reveal the following major themes in accessibility, acceptability, engagement, and self-efficacy.

First, it appears that the PwD were able to interact with the tablet and the game was acceptable to them and they even enjoyed playing it as indicated by the following:

> *"Thanks for choosing me to play the game." C.*
>
> *"I will recommend it to all my friends." G.*
>
> *"It was lovely." C.*

The enjoyment was not dependent on cognitive ability or on getting the correct answer. This was even the case with PwD who performed poorly on the game. For example, one woman would sing along with the game with a smile on her face even when she did not get the correct answer. Healthy older adults, on the other hand, found the game too easy, and on the most part not highly engaging.

In addition, we have some preliminary qualitative indicators that PwD's self-efficacy was improved. Quotes from the PwD expressed a sense of self-worth and an increase in their self-esteem with the use of the game as the testers heard quotes such as

> *"I did it!" M.*
>
> *"Now I know what utensil goes with what" M.*

Increase in self-reported self-efficacy was found and seen with PwD only, and not reported by the healthy community dwelling older adults.

The PwD were able to remember certain game components, both those that were easy for them and those that were more difficult, as demonstrated from this spontaneous comment from a PwD to the tester accompanying him: *"I can play the game, except for one that is a bit harder."* C.

We observed learning and special learning techniques used by the PwD in order to progress in the game. For example, one tester overheard the PwD speak to the tablet, which asked him for the answer for a second time saying, *"I know, I know, I am working on it."* C. He expressed the fact that he was thinking and interacting with the tablet.

Testers observed that auditory cueing improved PwD's performance and engagement with the game.

Figure 3. Average speed in seconds of successful screen completion for people with dementia and controls.

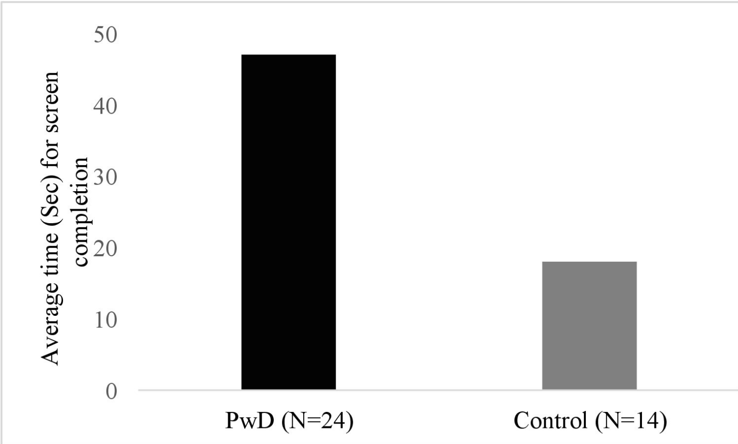
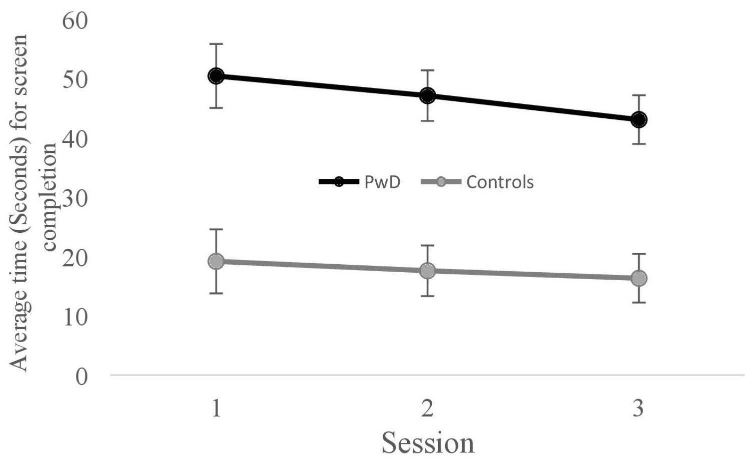


Figure 4. Average speed in seconds of successful screen completion for people with dementia and controls as a function of practice in the first three sessions.



Discussion

Relevance of Our Findings

The field of serious games for PwD is in its infancy. Our paper reporting on a research and development project aims to add much needed initial knowledge in this area. In relation to our original research questions, we learned that: (1) serious computer games can be acceptable and accessible to PwD; (2) people with moderate and advanced dementia are able to use a tablet; and (3) PwD improved in their speed of successful screen completion with practice, at a non-significantly different rate than healthy older adults, implying some form of significant learning occurred (see Figure 4).

From qualitative analysis of PwD spontaneous comments, we learned that PwD enjoyed using the game. Our findings are consistent with previous research suggesting that technology can be empowering and satisfying to participants [110].

Although it is generally assumed that PwD cannot learn new information and skills, our exploratory data show that some of those who used the game learned how to do many of its activities. Future research will test exactly what is learned in the game, and more importantly, if there is a transfer of knowledge from the game to real life scenarios over time.

There are several additional key themes that emerged in this pilot study that may be useful for clinical intervention and future game design. First, from the observations of the occupational therapists it appears that PwD can use a tablet better than a laptop. It was found to be easier for them to manipulate [111], as they can adjust it and hold it with minimal difficulties. Indeed, the touch screen response mode is easier than a mouse or keyboard [112]. Second, the testers observed that auditory cueing improves PwD's performance, supporting some of the findings in the literature [113-115].

Finally, it was encouraging to see that even people with dementia, who at the outset were hesitant to play the game, also had a positive interaction with the technology. Specifically, PwD who initially said that “this is not for me” because “I don’t know anything about tablets,” reported enjoying the game after their initial trial session and learning how to interact with it.

Limitations

This initial exploration has several limitations. The sample size was small, the duration was rather short, and not all the testers involved in the pilot were independent from the game development process. We also acknowledge that, in this stage, it is not possible to point out which of the factors considered during the development had the most effect on the results.

Comparison With Prior Work

Mccallum and Boletsis [116] in their literature review of dementia-related serious games reported a proliferation of cognitive training, exercise, and social games targeting dementia as well as its various symptoms. They conclude that serious games for dementia have a real effect on PwD, but the field is still “unchartered.” Robert and colleagues [117] recommend that serious games, adapted specifically for PwD, may constitute an important tool to maintain autonomy. Kenigsberg and colleagues [118] elaborate saying that “by providing pleasurable activities and person empowerment, these games are a way to enter the homes of PwD through technology, to structure collaborative care knowledge related to dementia and to educate stakeholders so they can cope with critical situations in everyday life.” Establishing links between behavioral disorders and their causes could help a personal or virtual coach in developing a care plan and lifestyle training. They close by stating, that the role of technology in improving sensory impairments and facilitating activities of daily living and providing positive experiences is underexplored. Our work is based on these previous studies and recommendations and focuses primarily on facilitating activities of daily living and providing positive experiences for PwD. This area has not been hitherto sufficiently researched.

Conclusion and Future Work

Based on both qualitative and quantitative analyses, our pilot, proof of concept study demonstrates that our game was acceptable, accessible, enjoyable, and engaging for PwD. We believe that this type of game set may be useful in creating activities for people with moderate to advanced dementia. These types of serious games may provide meaningful activities for the dyad—PwD and the caregivers of PwD. Such games may also be a good way to assess cognitive status of PwD in a nonthreatening way [119-123]. Future work should also consider cultural and language aspects that may affect performance and engagement (for a discussion, see [124]), as well as aspects of the testers themselves [125].

The significant improved speed for task completion may also suggest that the theoretical methodology used in constructing the game screens is suitable for PwD as it utilizes their remaining capacities - implicit memory and stimulates learning. Our future goal is to expand the game activities based on our holistic theory driven matrix. We aim to add more game screens and be able to study the transferability effect from game screens to functionality in real life scenarios. We plan to develop a training manual for professional and family caregivers related to how to use the game and deploy the package in a large practical trial with PwD living in the community setting. Finally, to test the game’s efficacy, we wish to evaluate, through a randomized trial, the trajectories of functionality in people with moderate to advanced dementia and the impact of playing the game on this trajectory.

Acknowledgments

We would like to thank the Israeli Ministry of Economy, Office of the Chief scientist, and the Israeli Ministry of Immigrant Absorption, new immigrant Scientists for helping to fund this research. We would also like to thank our medical student, Ayala Farkash, and our occupational therapy student, Sari Reichman, for help with this research.

Conflicts of Interest

None declared.

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Abbreviations

ADL: activities of daily living
HCD: human centered design
ISO: international standardization organization
ICT: information and communication technology
MCI: moderate cognitive impairment
MOCA: Montreal Cognitive Assessment
MMSE: mini mental state examination

PwD: people with dementia

Edited by G Eysenbach; submitted 21.08.16; peer-reviewed by S Ballesteros, L Quinlan, C Smits; comments to author 05.12.16; revised version received 26.03.17; accepted 26.05.17; published 31.07.17.

Please cite as:
Tziraki C, Berenbaum R, Gross D, Abikhzer J, Ben-David BM
Designing Serious Computer Games for People With Moderate and Advanced Dementia: Interdisciplinary Theory-Driven Pilot Study
JMIR Serious Games 2017;5(3):e16
URL: http://games.jmir.org/2017/3/e16/
doi:10.2196/games.6514
PMID:28760730

Original Paper

Domiciliary VR-Based Therapy for Functional Recovery and Cortical Reorganization: Randomized Controlled Trial in Participants at the Chronic Stage Post Stroke

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Abstract

Background: Most stroke survivors continue to experience motor impairments even after hospital discharge. Virtual reality-based techniques have shown potential for rehabilitative training of these motor impairments. Here we assess the impact of at-home VR-based motor training on functional motor recovery, corticospinal excitability and cortical reorganization.

Objective: The aim of this study was to identify the effects of home-based VR-based motor rehabilitation on (1) cortical reorganization, (2) corticospinal tract, and (3) functional recovery after stroke in comparison to home-based occupational therapy.

Methods: We conducted a parallel-group, controlled trial to compare the effectiveness of domiciliary VR-based therapy with occupational therapy in inducing motor recovery of the upper extremities. A total of 35 participants with chronic stroke underwent 3 weeks of home-based treatment. A group of subjects was trained using a VR-based system for motor rehabilitation, while the control group followed a conventional therapy. Motor function was evaluated at baseline, after the intervention, and at 12-weeks follow-up. In a subgroup of subjects, we used Navigated Brain Stimulation (NBS) procedures to measure the effect of the interventions on corticospinal excitability and cortical reorganization.

Results: Results from the system's recordings and clinical evaluation showed significantly greater functional recovery for the experimental group when compared with the control group (1.53, SD 2.4 in Chedoke Arm and Hand Activity Inventory). However, functional improvements did not reach clinical significance. After the therapy, physiological measures obtained from a subgroup of subjects revealed an increased corticospinal excitability for distal muscles driven by the pathological hemisphere, that is, abductor pollicis brevis. We also observed a displacement of the centroid of the cortical map for each tested muscle in the damaged hemisphere, which strongly correlated with improvements in clinical scales.

Conclusions: These findings suggest that, in chronic stages, remote delivery of customized VR-based motor training promotes functional gains that are accompanied by neuroplastic changes.

Trial Registration: International Standard Randomized Controlled Trial Number NCT02699398 (Archived by ClinicalTrials.gov at https://clinicaltrials.gov/ct2/show/NCT02699398?term=NCT02699398&rank=1)

(JMIR Serious Games 2017;5(3):e15) doi:10.2196/games.6773

KEYWORDS

stroke; movement disorder; recovery of function, neuroplasticity; transcranial magnetic stimulation; physical therapy; hemiparesis; computer applications software

Introduction

After initial hospitalization, many stroke patients return home relatively soon despite still suffering from impairments that require continuous rehabilitation [1]. Therefore, ¼ to ¾ of patients display persistent functional limitations for a period of 3 to 6 months after stroke [2]. Although clinicians may prescribe a home exercise regimen, reports indicate that only one-third of patients actually accomplish it [3]. Consequently, substantial gains in health-related quality of life during inpatient stroke rehabilitation may be followed by equally substantial declines in the 6 months after discharge [4]. Multiple studies have shown, however, that supported discharge combined with at home rehabilitation services does not compromise clinical inpatient outcomes [5-7] and may enhance recovery in subacute stroke patients [8]. Hence, it is essential that new approaches are deployed that help to manage chronic conditions associated with stroke, including domiciliary interventions [9] and the augmentation of current rehabilitation approaches in order to enhance their efficiency. There should be increased provision of home-based rehabilitation services for community-based adults following stroke, taking cost-effectiveness, and a quick family and social reintegration into account [10].

One of the latest approaches in rehabilitation science is based on the use of robotics and virtual reality (VR), which allow remote delivery of customized treatment by combining dedicated interface devices with automatized training scenarios [10-12]. Several studies have tested the acceptability of VR-based setups as an intervention and evaluation tool for rehabilitation [13-15]. One example of this technology is the, so called, Rehabilitation Gaming System (RGS) [16], which has been shown to be effective in the rehabilitation of the upper extremities in the acute and the chronic phases of stroke [13]. However, so far little work exists on the quantitative assessment of the clinical impact of VR based approaches and their effects on neural reorganization that can directly inform the design of these systems and their application in the domiciliary context. The main objective of this paper is to further explore the potential and limitations of VR technologies in domiciliary settings. Specifically, we examine the efficacy of a VR-based therapy when used at home for (1) assessing functional improvement, (2) facilitating functional recovery of the upper-limbs, and (3) inducing cortical reorganization. This is the first study testing the effects of VR-based therapy on cortical reorganization and corticospinal integrity using NBS.

Methods

Design

We conducted a parallel-group, controlled trial in order to compare the effectiveness of domiciliary VR-based therapy versus domiciliary occupational therapy (OT) in inducing functional recovery and cortical reorganization in chronic stroke patients.

Participants

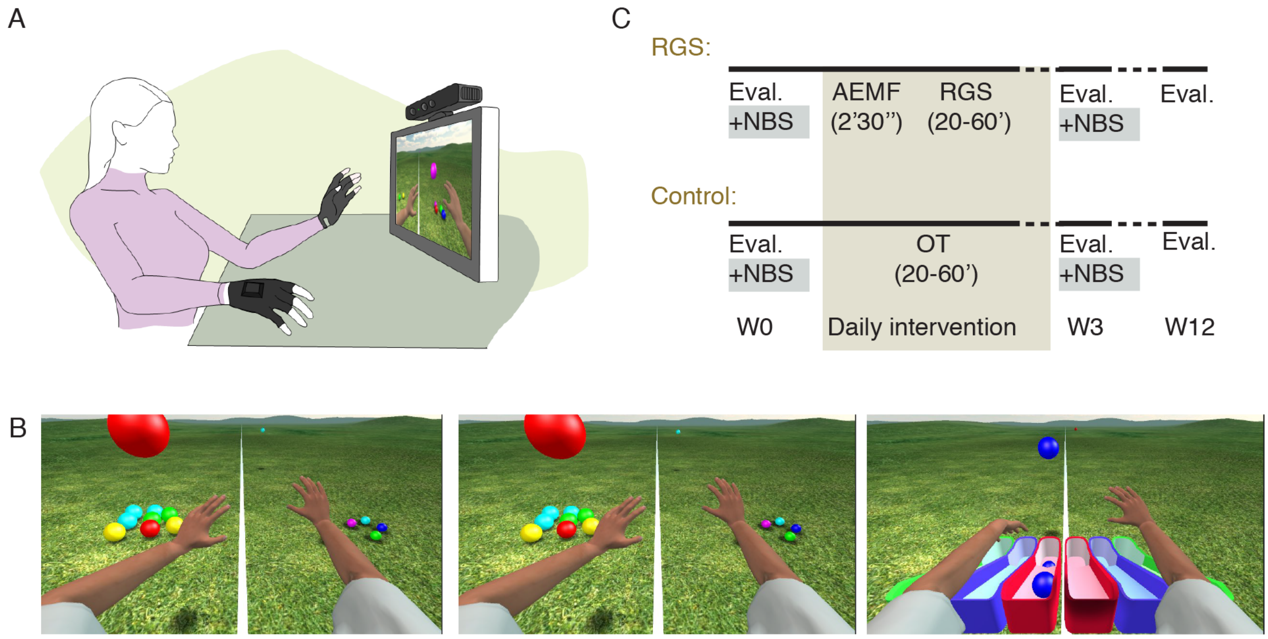
Participants were first approached by an occupational therapist from the rehabilitation units of Hospital Esperanza and Hospital Vall d'Hebron from Barcelona to determine their interest in participating in a research project. Recruited participants met the following inclusion criteria: (1) mild-to-moderate upper-limbs hemiparesis (Proximal MRC>2) secondary to a first-ever stroke (>12 months post-stroke), (2) age between 45 and 85 years old, (3) absence of any major cognitive impairment (Mini-Mental State Evaluation, MMSE>22), and (4) previous experience with RGS in the clinic. The ethics committee of clinical research of the Parc de Salut Mar and Vall d'Hebron Research Institute approved the experimental guidelines. Thirty-nine participants at the chronic stage post-stroke were recruited for the study by two occupational therapists, between October 2011 and January 2012, and were assigned to a RGS (n=20) or a control group (n=19) using stratified permuted block randomization methods for balancing the participants' demographics and clinical scores at baseline (Table 1). One participant in the RGS group refused to participate. Prior to the experiment, participants signed informed consent forms. This trial was not registered at or before the onset of participants' enrollment because it is a pilot study that evaluates the feasibility of a prototype device. However, this study was registered retrospectively in ClinicalTrials.gov and has the identifier NCT02699398.

Instrumentation

Description of the Rehabilitation Gaming System

The RGS integrates a paradigm of goal-directed action execution and motor imagery [17], allowing the user to control a virtual body (avatar) through an image capture device (Figure 1). For this study, we developed training and evaluation scenarios within the RGS framework. In the Spheroids training scenario (Figure 1), the user has to perform bilateral reaching movements to intercept and grasp a maximum number of spheres moving towards him [16]. RGS captures only joint flexion and extension and filters out the participant's trunk movements, therefore preventing the execution of compensatory body movements [18]. This task was defined by three difficulty parameters, each of them associated with a specific performance descriptor: (1) different trajectories of the spheres require different ranges of joint motion for elbow and shoulder, (2) the size of the spheres require different hand and grasp precision and perceptual abilities, and (3) the velocity of the spheres require different movement speeds and timing. All these parameters, also including the range of finger flexion and extension required to grasp and release spheroids, were dynamically modulated by the RGS Adaptive Difficulty Controller [19] to maintain the performance ratio (ie, successful trials over the total trials) above 0.6 and below 0.8, optimizing effort and reinforcement during training [20].

Figure 1. Experimental setup and protocol: (A) Movements of the user's upper limbs are captured and mapped onto an avatar displayed on a screen in first person perspective so that the user sees the movements of the virtual upper extremities. A pair of data gloves equipped with bend sensors captures finger flexion. (B) The Spheroids is divided into three subtasks: hit, grasp, and place. A white separator line divides the workspace in a paretic and non-paretic zone only allowing for ipsilateral movements.(C) The experimental protocol. Evaluation periods (Eval.) indicate clinical evaluations using standard clinical scales and Navigated Brain Stimulation procedures (NBS). These evaluations took place before the first session (W0), after the last session of the treatment (day 15, W3), and at follow-up (week 12, W12).



Description of the Evaluation Scenario

Designing automated evaluation tools to be used at-home in a non-supervised setup could provide objective and frequent measurements of recovery, offering valuable information to clinicians and primary users, and driving autonomous rehabilitation technologies. We, therefore, developed the Automated Evaluation of Motor Function (AEMF), a VR-based evaluation scenario for the assessment of upper-limb motor function that was designed to operate under non-supervised conditions.

Description of the Automated Evaluation of Motor Function (AEMF)

In order to assess proximal and distal motor function, the AEMF scenario is divided into two separated tasks. In task 1, participants were asked to perform planar wiping movements with their arms to clear a virtual surface covered with small cubes. In task 2, participants were instructed to squeeze a virtual object by flexing and extending their fingers. In order to guarantee that the AEMF tasks were correctly understood, each of these was first performed using the non-paretic limb and then with the paretic limb. Participants did not receive any explicit feedback (ie, knowledge of results) about their overall performance. During task execution, we collected data of hand position and joint rotation (fingers, elbows, and shoulders) to compute three main performance descriptors: the horizontal planar area covered, finger flexion, and extension.

Experimental Protocol

In order to test the effectiveness of VR in the domiciliary context, each participant received daily home-based upper-limb rehabilitation during 5 weekly days, for 3 consecutive weeks. The RGS group followed a home-based training paradigm based on the Spheroids scenario (Figure 1), comprising 3 consecutive subtasks: Hit, Grasp, and Place, with a total duration of 20 minutes, 6 minutes, and 40 seconds each. Participants in the RGS group completed the Automated Evaluation of Motor Function once a day, before the training session, which lasted 2 minutes and 30 seconds. We delivered the system and trained the participants and their corresponding caregivers to use the system without supervision. The control group performed a 20 minutes OT task at home, without assistance, which consisted of horizontal and vertical stacking and unstacking of plastic cups with their right and left hand consecutively. This task was designed by an occupational therapist to match the movements trained during the RGS task. At the end of the therapy, the participants reported to have completed a minimum of 1 session a day. In the RGS group, the therapy time was similarly split between 10 minutes of activity with the affected hand and 10 minutes with the less affected hand. All participants were asked to perform a minimum of 1 and a maximum of 3 training sessions a day.

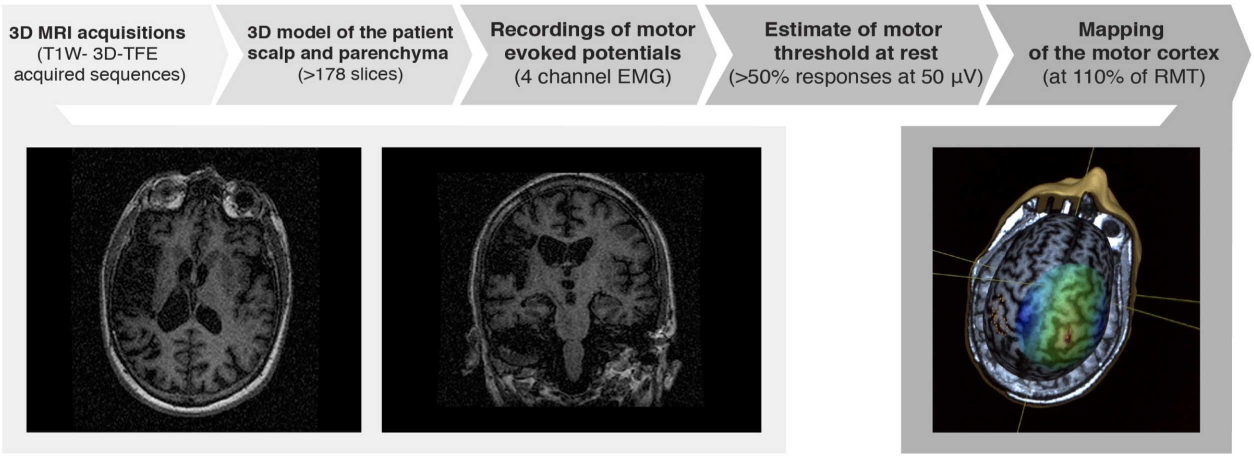
Outcome Measures

All participants' motor function was evaluated at day 1, day 15 of the rehabilitation program, and week 12 follow-up (Figure 1), using 8 standard clinical scales. Evaluations were carried out by two occupational therapists who were not blinded to treatment assignment. Primary outcomes were the improvement in the upper extremity section of the Fugl-Meyer Assessment (UE-FM) [21], and the Chedoke Arm and Hand Activity Inventory (CAHAI) [22]. Secondary outcomes were improvements in Barthel Index (BI) [23], Ashworth Scale for distal (ASd) and proximal upper limb (ASp) [24], Medical Research Council Scale for distal (MRCd) and proximal upper limb (MRCp) [25], and grip force. In addition, we used the Hamilton Scale to assess mood disorders [26], and the Visual Analog Scale (VAS) to evaluate shoulder pain [27].

Both during the training and evaluation sessions, we captured the user's movements and mapped them onto a biomechanical model of the upper limbs. Specifically, virtual movements were controlled by the angles of the users' joints measured by a motion capture device at 30Hz (Kinect, Microsoft, USA). The range of finger flexion was captured by a pair of data gloves (DGTech Engineering Solutions, Bazzano, Italy) equipped with bend sensors, measures range from 0 to 1, indicating maximum extension and maximum flexion respectively.

Navigated Brain Stimulation (NBS) procedures [28] were used to assess training-induced changes in the functional integrity of the pyramidal tract and cortical maps in the primary motor area (M1). A total of 17 participants (3 of them assigned to the control group) accepted to participate in the NBS procedure, which was conducted for each subject before and after treatment (Figure 2). A 3-Tesla magnet (Philips Achieva) was used for 3D MRI acquisitions. In order to faithfully build a 3D model of the participant's scalp and parenchyma we used T1W-3D-TFE acquired sequences comprising a minimum of 178 slices. For nTMS mapping we used a butterfly coil (MC-B70, Medtronic, Alpine, USA), and magnetic stimulation equipment (Mag Pro-30 with MagOption, Medtronic, Alpine, USA) synchronized with a three-dimensional tracking system (Navigated Brain System, Nexstim, Eximia, Finland). Motor evoked potentials (MEPs) were recorded using surface electrodes (Ambu, Neuroline 700), connected to a 4 channel electromyographic (EMG) system (Key-Point net, Medtronic, USA). Data collected during NBS was analyzed to estimate the motor threshold at rest (RMT) for abductor pollicis brevis (APB) and extensor-carpi radialis (ECR) for each participant. The RMT was defined as the intensity of TMS stimulus needed to obtain more than 50% of responses with amplitudes over 50 µV. After finding the RMT of both muscles we proceeded to draw the cortical maps of both the healthy and pathological hemisphere in each participant. Maps were drawn at 110% of RMT, a percentage commonly used to avoid no-response spots and suppressive effects. When no-response was found on the pathological side we incremented the stimulus intensity stepwise in a logarithmic fashion (ie, 110%, 120%, and 140%) until the maximum stimulator output was reached. To determine the boundaries, we stopped searching a particular direction until two no-response points aligned in the same vector and direction or when the sulcus boundaries were reached. After processing the data, we characterized cortical representations of APB and ECR and corticospinal connectivity in each cerebral hemisphere by estimating the centroid of the cortical motor output map and their corresponding Stimulation Efficacy (SE). SE was the greatest value in the 80th percentile of the MEPs divided by the maximum stimulation intensity.

Figure 2. Navigated Brain Stimulation (NBS) procedure. Bottom right: axial and coronal view of a magnetic resonance imaging (MRI) scan at the level of the stroke for one of the participants in the experimental group showing a partial anterior circulation infarct due to an embolism. Bottom right: Example of NBS mapped cortical motor representations; colored areas indicate the targeted cortical sites.



Data Analysis

For statistical analysis, data were tested for normality using the Kolmogorov-Smirnov test. To identify significant time effects on clinical scores we performed a Friedman test. Next, we conducted a post-hoc analysis using 2-tailed Mann-Whitney *U* tests to compare improvements between groups at week 3 and week 12 follow-up. Within-subject analysis of recovery was assessed using standard clinical scales (Table 1). We reversed the polarity of Hamilton, VAS and Ashworth scales so that positive changes on all scales would express recovery.

In order to validate the RGS Adaptive Difficulty Controller, automatic performance ratios and difficulty parameters assigned by RGS to the paretic and non-paretic limb were compared (Wilcoxon signed-rank test). Next, to explicitly study progress in performance, we averaged values for each difficulty parameter per session and performed a within-subjects time-series analysis of the means (Friedman test).

Data of hand position and joint rotation collected during performance in AEMF were filtered using a second order Butter-worth low- pass filter (cut-off at 6 Hz) reducing noise. In order to assess the participant's motor function within AEMF, we calculated three performance descriptors for each extremity:

(1) the work area was defined as the dorsal surface area of the movement space, while (2) finger flexion, and (3) extension were defined as the maximal and minimal metacarpal angles respectively, averaged across all fingers.

We tested AEMF sensitivity by examining between-limbs differences in descriptor values (ie, covered area, finger flexion and finger extension) for each subject (Wilcoxon signed-rank test). Next, in order to explore AEMF test-retest stability and sensitivity to capture improvement, we analyzed changes in descriptor values across sessions (Friedman test). In addition, we studied the relation between standardized clinical scores and AEMF measurements of motor function by computing a Spearman correlation coefficient for each descriptor and clinical scale at the corresponding evaluation period.

Finally, we compared the Stimulation Efficacy (SE) and the centroid location of the cortical motor areas representing APB and ECR in M1, for the pathological and non-pathological hemispheres (Wilcoxon sign-sum test). In order to extract training effects, we performed a within-subject analysis of the Stimulation Efficacy and the centroid location of the cortical maps in M1 before and after treatment (Wilcoxon sign-sum test). We used a Spearman test to study the correlations between NBS outcome measures and improvements in clinical scales.

Two-sided significance level for all statistical tests was defined as alpha=0.05.Data processing and statistical analysis were performed using Matlab 2013a (MathWorks, Inc.). Due to limited statistical power, we did not correct for multiple comparisons.

Table 1. Participants' demographics and scores from clinical scales at baseline.

Demographics	RGS (n=17)	Control (n=18)	*P* value
Gender (female), n (%)	9 (53)	12 (67)	.59[a]
Age, mean (SD)	65.05 (10.33)	61.75 (12.94)	.44[b]
Affected side (left), n (%)	11 (65)	9 (50)	.58[a]
Type (hemorrhagic), n (%)	6 (33)	6 (33)	.81[a]
Oxford class (LAC[c]/PAC[d]/TAC[e])	4/3/4	6/2/4	.65[a]
Days after stroke, mean (SD)	1073.43 (767.74)	798.06 (421.80)	.64[b]
MMSE [16], mean (SD)	28.24 (2.33)	28.22 (2.34)	.08[b]
Hamilton [17], mean (SD)	3.71 (3.35)	4.56 (3.24)	.40[b]
Grip force, mean (SD)	6.15 (5.04)	5.94 (5.85)	.69[b]
MRC[f] proximal [19], mean (SD)	3.47 (0.51)	3.39 (0.61)	.76[b]
MRC distal [19], mean (SD)	2.82 (1.19)	3.17 (0.99)	.44[b]
FMA [20], mean (SD)	42.94 (14.37)	43.44 (13.48)	.89[b]
CAHAI[g] [21], mean (SD)	52.82 (23.10)	53.50 (22.51)	.95[b]
Barthel [22], mean (SD)	89.53 (9.43)	84.72 (14.19)	.48[b]
Ashworth proximal [23], mean (SD)	1.24 (1.25)	1.22 (1.31)	.97[b]
Ashworth distal [23], mean (SD)	1.47 (1.51)	1.00 (1.41)	.42[b]
VAS[h] shoulder [16], mean (SD)	1.59 (2.76)	2.61 (2.64)	.13[b]

[a]Chi-square test.

[b]Wilcoxon rank-sum test.

[c]LAC: Lacunar stroke.

[d]PAC: Partial anterior circulation stroke.

[e]TAC: Total anterior circulation stroke.

[f]MRC: Medical Research Council.

[g]CAHAI: Chedoke Arm and Hand Activity Inventory (version CAHAI-13).

[h]VAS: Visual Analog Scale.

Results

Benefits of At-Home VR-Based Training on Motor Recovery

In order to assess the impact of the RGS treatment, we conducted a repeated measures analysis of the functional recovery captured through standardized clinical scales. Analysis of participants' demographics revealed no significant differences between groups at baseline (Table 1). Comparing the change between baseline and week 3 in clinical scores we detected a significant difference on the CAHAI scale (Table 2). The RGS group showed significant improvements in CAHAI as compared to the control group (*P*=.05, Wilcoxon signed-rank test, Table 2). A post-hoc power analysis was conducted to determine the power of this statistical comparison for the sample size n=17. A medium effect size, d=0.48, at alpha=0.05 reached a low power level (Beta=0.4). A within-subjects analysis on the RGS group revealed an average improvement of 1.53 (SD 2.4) points on the CAHAI scale (*P*=.03, Wilcoxon signed-rank test); however, these effects did not persist at the week 12 follow-up evaluation. At follow-up we observed a significant difference between groups in improvement on the Ashworth scale only for distal muscle groups (*P*=.03, power=0.6, Wilcoxon signed-rank test), however, this difference did not reach statistical significance after Bonferroni correction.

Progress of Performance in VR

Participants in the RGS group completed a variable total number of Hit (37.1, SD 18.4), Grasp (35.1, SD 17.0) and Place (34.2, SD 16.8) subtasks along the 3 weeks of treatment. All patients participating in the study were able to put the gloves on with assistance, and autonomously set-up and use the system until finishing the game. In order to assess whether the adaptive difficulty controller effectively provided customized training intensities that matched the participants' capabilities, we explored inter-limb differences in mean performance ratios during training. Differences in performance showed a trend toward significance in Grasp and Place subtasks (*P*<.06, Wilcoxon). Notice that in order to provide an optimal training challenge for the user, the RGS system dynamically adjusted the difficulty parameters for each arm, mean performance ratios were maintained around 0.7 for each limb, across all tasks and sessions. Therefore these differences in performance between limbs may uncover existing floor effects in the difficulty adaptation algorithm for those participants unable to achieve complete power grasp movements [19]. In line with these findings, a within-subject analysis revealed a significant increase in the range and size difficulty coefficients assigned to the paretic limb during the Grasp and Place task across sessions (*P*<.05, Friedman). Similar improvements were observed for the non-paretic limb during the Hit and the Grasp subtasks.

Automated Evaluation of Motor Function

In order to study the RGS AEMF sensitivity, we compared measurements for the paretic and non-paretic limb. In addition, we explored the test-retest stability of these parameters. We observed that estimates of working area and maximal finger extension performed by the paretic limb in AEMF were significantly lower when compared to the non-paretic limb (*P*<.01, Wilcoxon). Within-subjects analysis showed no effect of time in the work area for the non-paretic (*P*=.06, Friedman), and a significant effect for the paretic limb (*P*=.03, Friedman). Post-hoc analysis revealed that these gains occurred during week 3 (*P*<.01, Wilcoxon). We also found a significant effect of time on maximum finger flexion for the paretic limb (*P*=.006, Friedman), which occurred at week 2 and 3 (*P*<.01, Wilcoxon, Figure 3). In order to validate AEMF, we correlated its measurements with assessments from standard clinical scales (Table 2). We used AEMF-derived improvement descriptors to fit scores from the CAHAI scale. An optimal fit was achieved by the sum of maximal finger flexion and extension (R-squared=.602, *P*<.001).

Figure 3. A: AEMF captures an improvement in finger flexion during treatment. Averaged movement profile of fingers excursion performed by one subject during one of the sessions. Units of finger flexion are expressed as a ratio of complete flexion. B: Mean changes in maximal finger flexion for all subjects in the RGS group across the three weeks of intervention, for both non-paretic (NPL) and paretic limbs (PL).

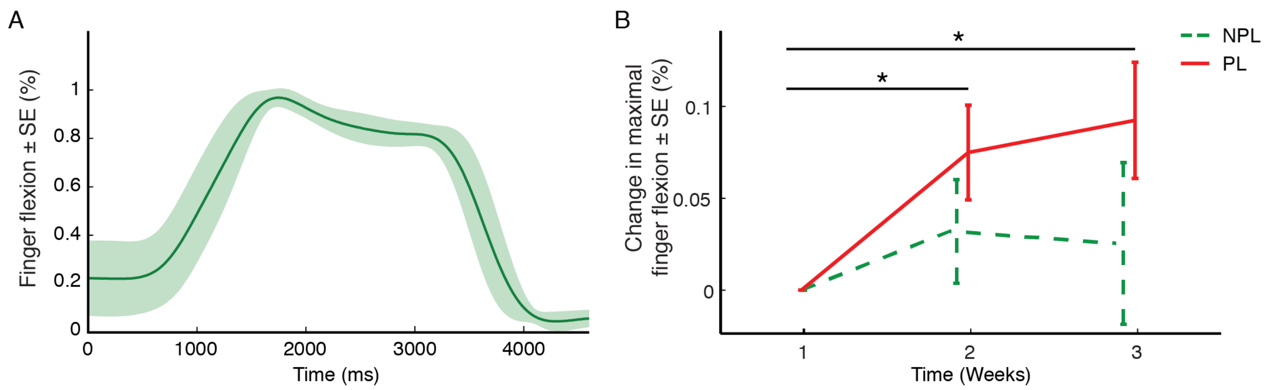


Table 2. Effects of RGS treatment versus control on clinical scales within and between groups for the post treatment assessment at week 3 and the long-term follow up at week 12.

Assessment	RGS (n=17)		Control (n=18)		Between Groups	Effect size
	Improvement, mean (SD)	*P*	Improvement, mean (SD)	*P*	*P*	Cohen *d*
End (Week 3)						
UE-FM[a]	0.35 (1.62)	.43	1.22 (3.84)	.15	.33	−0.30
CAHAI[b]	1.53 (2.4)	.01	−0.67 (6.01)	.90	.05	0.48
Barthel	0.00 (1.87)	>.99	1.00 (2.87)	.25	.44	−0.41
MRCp[c]	0.06 (0.24)	>.99	0.11 (0.32)	.50	.61	−0.17
MRCd[d]	0.06 (0.43)	>.99	0.11 (0.47)	.63	.74	−0.12
Asp[e]	0.00 (0.35)	>.99	0.06 (0.24)	>.99	.32	0.40
Asd[f]	0.12 (0.33)	.50	0.00 (0.34)	>.99	.32	0.36
Grip force	0.41 (1.78)	.89	0.38 (2.65)	.47	.57	0.01
Hamilton	0.88 (2.45)	.16	0.67 (1.57)	.13	.66	0.10
VAS-S[g]	0.41 (1.81)	.05	−0.28 (1.90)	.69	.63	0.37
Follow-up (Week 12)						
UE-FM	−0.18 (3.50)	.82	1.39 (3.63)	.11	.21	0.34
CAHAI	−0.06 (6.51)	.74	0.44 (5.46)	.67	.61	−0.08
Barthel	−3.30 (8.09)	.29	−0.11 (3.98)	.92	.74	−0.50
MRCp	−0.12 (0.78)	>.99	0.28 (0.46)	.06	.06	−0.62
MRCd	0.29 (0.77)	.25	0.17 (0.62)	45	.98	−0.17
Asp	0.06 (0.65)	>.99	0.00 (0.34)	>.99	>.99	−0.12
Asd[f]	0.29 (0.59)	.13	0.00 (0.00)	>.99	.03	0.70
Grip force	0.21 (1.45)	.73	0.23 (3.02)	.92	.93	−0.01
Hamilton	0.35 (2.34)	.70	1.11 (3.53)	.42	.93	−0.25
VAS-S	0.12 (2.06)	.92	0.78 (3.08)	.38	.27	−0.25

[a]UE-FM: The upper extremity Fugl-Meyer Assessment.
[b]CAHAI: Chedoke Arm and Hand Activity Inventory (version CAHAI-13).
[c]MRCp: Medical Research Council for proximal muscles.
[d]MRCd: Medical Research Council for distal muscles.
[e]Asp: Ashworth Scale for proximal muscles.
[f]Asd: Ashworth Scale for distal muscles.
[g]VAS-S: Visual Analog Scale for Shoulder Pain.

RGS Induced Changes in the Corticospinal System

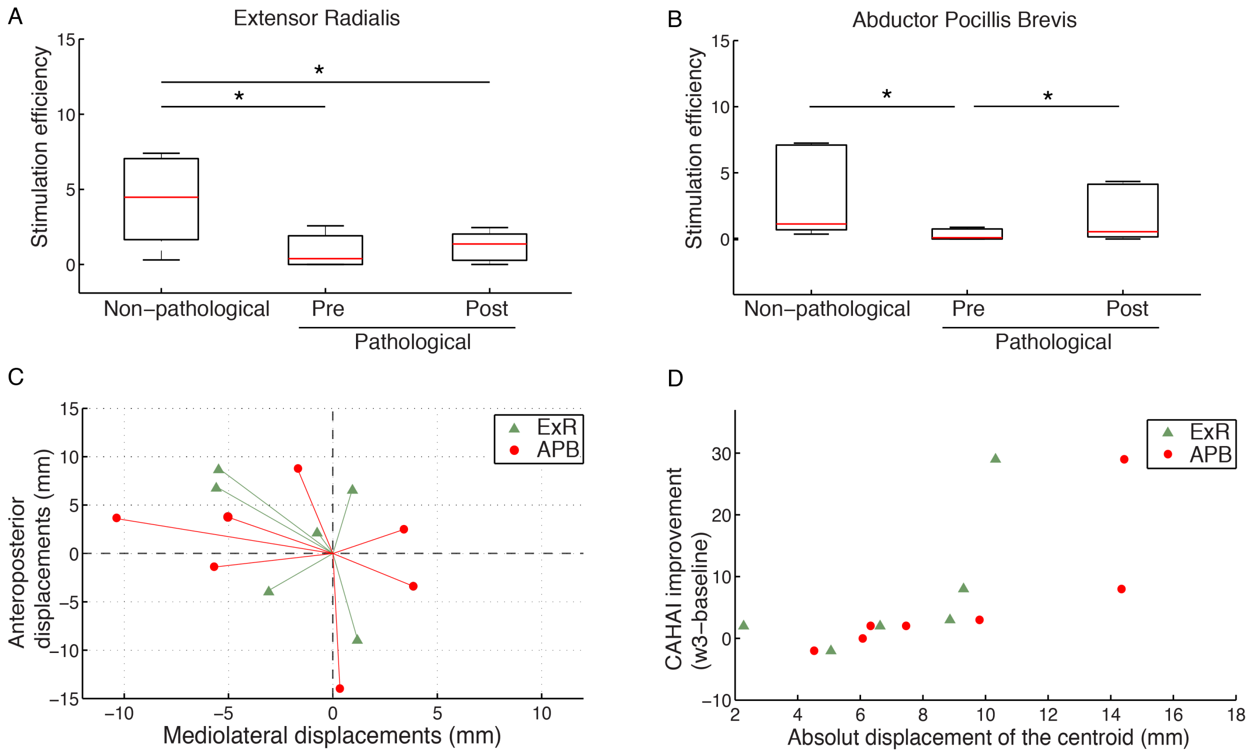
In order to detect training-induced changes in the corticospinal system, we first characterized cortical regions in the primary motor area of the pathological and non-pathological hemispheres representing abductor pollicis brevis (APB) and extensor-carpi radialis (ECR) muscles. At baseline, the Stimulation Efficacy (SE) was significantly higher for the non-pathological hemisphere when compared to the pathological one (*P*<.01, Wilcoxon) (Figure 4). We observed that the centroid of the cortical area that produced MEPs was different between hemispheres along the mediolateral, and the anteroposterior axis (*P*<.05, Wilcoxon). In the non-pathological hemisphere, the cortical substrate representing the ECR was significantly larger than the area corresponding to the APB muscle (*P*<.05, Wilcoxon). Interestingly, this difference was not present in the pathological hemisphere.

SE increased significantly within subject after treatment in the pathological hemisphere (3.6, SD 8.60; *P*<.01, Wilcoxon). This change was significant only for the RGS group (4.17, SD 9.86;

P<.01, Wilcoxon; *d*=.6) and the APB muscle (5.21, SD 10.98; *P*=.05, Wilcoxon; *d*=.66) [29].

We observed a centroid displacement in the pathological hemisphere, which occurred after treatment both for the APB and the ECR muscle (Figure 4). Since changes in cortical organization may indicate actual motor gains, we correlated post-treatment changes in SEs and centroid displacements with improvements at week 3 that were captured by the clinical scales [30]. Changes in SEs for the APB muscle strongly correlated with improvements in UE-FM (r_s=.86, *P*<.01) (Figure 4), CAHAI (r_s=.92, *P*<.01), and Barthel (r_s=.68, *P*<.05), while the same effect was not present in the ECR muscle (r_s<.61, *P*>.14). In addition, centroid displacements measured after intervention for the APB muscle were strongly correlated with UE-FM (r_s=.87, *P*<.05), CAHAI (r_s=.99, *P*<.01), and Barthel (r_s=.81, *P*<.05). Centroid displacements for the ECR muscle also showed strong correlations with UE-FM (r_s=.99, *P*<.01), and CAHAI (r_s=.89, *P*<.05) clinical scales. Changes in the area of the cortical regions associated with each of the two muscles did not show any significant correlation with the improvements in clinical scales.

Figure 4. Effects of domiciliary rehabilitation therapy on corticospinal efficacy. (A) Change in mean Stimulation Efficacy for extensor-carpi radialis (ECR) in the damaged hemisphere (pathological) and the intact hemisphere (non-pathological). (B) Change in mean Stimulation Efficacy for abductor pollicis brevis (APB). (C) Centroid displacements after therapy along anterioposterior and mediolateral axis. (D) Correlation of absolute centroid displacements after therapy with improvement in CAHAI score after therapy.



Discussion

Principal Findings

We have studied the effectiveness of the RGS VR-based system for home-based motor rehabilitation of the upper extremities after stroke by conducting a controlled, longitudinal clinical trial assessing both functional and structural impact and comparing it to an OT task. We have shown that, at the chronic stage post-stroke, the remote delivery of customized self-managed motor training in VR environments may effectively induce motor gains and neuroplastic changes. Comparisons between groups suggest a superiority of VR compared with OT in domiciliary setups, however, this difference does not reach clinical impact. Our results highlight the potential of automated rehabilitation technologies for domiciliary neurorehabilitation, which so far has been an issue of some contention [31].

First, we validated the RGS Adaptive Difficulty Controller, which automatically provides for a limb specific customization of practice difficulty and intensity, and a progress-monitoring tool. We observed lower success rates during the execution of those subtasks involving distal movements (ie, Grasp and Place). Lateralized customization of task difficulty allowed for the maintenance of optimal performance levels for each limb across sessions. Within-subject analysis of the evolution of the difficulty parameters assigned during training revealed paretic limb specific functional improvements during a reaching and grasping task. These observations may indicate functional gains of distal function (ie, increased control in fingers flexion and extension). Data collected by the Automated Evaluation of Motor Function further confirmed these findings, revealing significant improvements for the paretic limb, during week 2 and 3, in finger flexion. Interestingly, we also found an improvement in range of movement both for the paretic and non-paretic limb, probably indicating a generalization of new cognitive and compensatory strategies. Notice that subjects included in this study were in the chronic phase of stroke (mean time post stroke 65.05 months, SD 10.3), a period in which motor improvements are supposed to have plateaued and limited non-compensatory functional gains can still be induced through further physical or OT [32]. We show that the RGS group displayed significant gains on the CAHAI scale as compared to control. However, these changes did not reach the minimal detectable change (MDC=6.3 points) and we observed no retention of the improvements at follow-up, suggesting that achievement and retention of clinically relevant improvements at the chronic stage post-stroke may depend on longer intervention periods [30]. We did not observe any significant changes in the UE-FM scale, in any of the groups, perhaps due to the lack of responsiveness of this scale at the chronic stage post-stroke [33]. An alternative explanation for the lack of effect in the UE-FM scale is that these improvements may be fundamentally related to compensatory changes at the Body Functions and Structure and Activity levels [34].

Results from the NBS protocol supported these findings by displaying an enhanced corticospinal excitability after treatment only for the more distal muscle (ABP) associated with hand function. In addition, we observed centroid displacements of the cortical map for both the ABP and the ECR. This confirms earlier reports that enhanced corticospinal excitability and cortical map centroid displacements strongly correlate with functional gains detected by standardized clinical scales, such as Fugl-Meyer, CAHAI, and Barthel scales [30,32,35-37]. Previous research suggests that an imaging measure of corticospinal tract (CST) injury in the acute phase can predict motor outcome at 3 months [38]. Our results show that NBS-derived measures of corticospinal connectivity may be also relevant biomarkers for identifying chronic stroke survivors who have the potential to respond to a particular rehabilitative therapy and may be predictive of patient prognosis. Overall, these plastic changes may be use-dependent; an increase in the use of the paretic limb during the intervention period may have unmasked preexisting excitatory connections or even enhanced the efficacy of existing neuronal networks. Thus, RGS-induced cortical changes could be related to a greater activation in the ipsilesional hemisphere, as has been proposed by previous studies [39,40].

Limitations

Taking a global perspective on these results, we observe that task difficulty descriptors, AEMF measurements, and NBS, converged, suggesting that distal functional improvements were induced through RGS based training and were significantly larger for those participants in the RGS group when compared with the control group. The reason why we may not have observed improvements in proximal muscle groups and other clinical scales may be related to the stringent inclusion criteria of the study, which excluded all subjects showing severe hemiparesis at baseline (Proximal Medical Research Council, MRC>2). It is widely known that the corticospinal system is organized following a proximal to distal gradient to the cervical spinal cord, where motoneurons of the distal muscle groups receive most input projections [41]. Due to this hierarchical organization, the severity of hemiparesis is often greatest in the distal muscles and least in the proximal muscles of the upper extremity [42]. Interestingly, this disparity may only appear at the chronic stage [18]. Consistent with these observations, participants showed a greater muscle weakness at baseline for distal than for proximal muscle groups (Table 1), which may be associated with a distal to proximal recovery process at this later stage post-stroke [43]. The specific factors involved in causing the observed RGS-derived improvements in distal function as compared to OT are not fully explained by our results. For instance, training in these two conditions differed in some aspects. On the one hand, RGS explicitly prevented the execution of compensatory body movements by capturing only joint flexion and extension and filtering out the participant's trunk movements [44]. In contrast, participants in the control group, who followed a domiciliary OT protocol, without any supervision, may not have reached sufficient training intensity or may have reinforced the execution of functional compensatory movements (eg, overusing the non-paretic limb or performing trunk displacements) [45]. On the other hand, participants assigned to the RGS group repeatedly performed goal-oriented visuomotor transformations in order to control the virtual analogue of their paretic and non-paretic limbs, which may induce increased neural activity in cortical motor areas [40,46]. Indeed, we have shown that in healthy controls exposure to the RGS scenario leads to significantly enhance activity in premotor areas [47]. The OT group, however, was not exposed to such transformations, indeed subjects in this group performed repetitive visuomotor tasks in the real world only, where visual exposure to motor movements performed with the paretic limb may not be critical for successful performance. Although these are factors that could be better controlled in OT, our objective was to achieve a fair comparison between RGS virtual reality based and standard domiciliary OT and to understand their relative impact. In addition to motor gains, we observed a reduction in shoulder pain in the VR group, captured by the VAS scale. The reason for this effect may be that the VR group did not have to perform repetitive movements at the shoulder joint, unlike the control group. This difference could also explain the trend in an increase in muscle strength for the proximal musculature in the control group.

Conclusions

In this randomized controlled study, we explored the effects of a VR-based system for domiciliary rehabilitation on functional recovery and cortical reorganization. Our results suggest that at-home VR-based rehabilitation promotes functional motor gains, enhances corticospinal excitability, and induces cortical reorganization at the chronic stage post- stroke. The observation of strong correlations between increased motor evoked potentials after treatment and functional gains in CAHAI suggests that exposure to VR-based goal-oriented motor training may have enhanced the organization of corticospinal pathways, facilitating distal motor control. The displacement of the centroid of cortical maps after training may also indicate related cortical reorganization at the chronic stage post-stroke supporting the idea that recovery can be induced at any stage post stroke albeit to varying degrees.

Acknowledgments

We would like to thank all subjects who participated in this study. We also would like to gratefully acknowledge Estefanía Montiel for her assistance in recruiting and evaluating the participants. This work was supported by the MINECO "Retos Investigacion tos Investigacion I + D + I" Plan Nacional project SANAR (Gobierno de España), and the European Research Council under grant agreement 341196 CDAC and FP7-ICT- 270212 project eSMC.

Conflicts of Interest

PV is involved in the spin-off company Eodyne Systems SL, which has the goal to achieve a large-scale distribution of science based rehabilitation technologies.

Multimedia Appendix 1

CONSORT eHealth form.

[PDF File (Adobe PDF File), 66KB - games_v5i3e15_app1.pdf]

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Abbreviations

AEMF: automated evaluation of motor function
APB: abductor pollicis brevis
ASd: Ashworth scale for distal upper limb
ASp: Ashworth scale for proximal upper limb
BI: barthel index
CAHAI: chedoke arm and hand activity inventory
ECR: extensor-carpi radialis
MMSE: mini-mental state evaluation
MRC: medical research council scale
NBS: navigated brain stimulation
OT: occupational therapy
RGS: rehabilitation gaming system
SE: simulation efficacy
UE-FM: the upper extremity Fugl-Meyer assessment
VAS: visual analog scale
VR: virtual reality

Edited by G Eysenbach; submitted 09.10.16; peer-reviewed by I Cikajlo, R Lloréns, D Putrino; comments to author 09.01.17; revised version received 04.04.17; accepted 29.04.17; published 07.08.17.

Please cite as:
Ballester BR, Nirme J, Camacho I, Duarte E, Rodríguez S, Cuxart A, Duff A, Verschure PF
Domiciliary VR-Based Therapy for Functional Recovery and Cortical Reorganization: Randomized Controlled Trial in Participants at the Chronic Stage Post Stroke
JMIR Serious Games 2017;5(3):e15
URL: http://games.jmir.org/2017/3/e15/
doi:10.2196/games.6773
PMID:28784593

Original Paper

Exergames Encouraging Exploration of Hemineglected Space in Stroke Patients With Visuospatial Neglect: A Feasibility Study

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Abstract

Background: Use of exergames can complement conventional therapy and increase the amount and intensity of visuospatial neglect (VSN) training. A series of 9 exergames—games based on therapeutic principles—aimed at improving exploration of the neglected space for patients with VSN symptoms poststroke was developed and tested for its feasibility.

Objectives: The goal was to determine the feasibility of the exergames with minimal supervision in terms of (1) implementation of the intervention, including adherence, attrition and safety, and (2) limited efficacy testing, aiming to document possible effects on VSN symptoms in a case series of patients early poststroke.

Methods: A total of 7 patients attended the 3-week exergames training program on a daily basis. Adherence of the patients was documented in a training diary. For attrition, the number of participants lost during the intervention was registered. Any adverse events related to the exergames intervention were noted to document safety. Changes in cognitive and spatial exploration skills were measured with the Zürich Maxi Mental Status Inventory and the Neglect Test. Additionally, we developed an Eye Tracker Neglect Test (ETNT) using an infrared camera to detect and measure neglect symptoms pre- and postintervention.

Results: The median was 14 out of 15 (93%) attended sessions, indicating that the adherence to the exergames training sessions was high. There were no adverse events and no drop-outs during the exergame intervention. The individual cognitive and spatial exploration skills slightly improved postintervention (P=.06 to P=.98) and continued improving at follow-up (P=.04 to P=.92) in 5 out of 7 (71%) patients. Calibration of the ETNT was rather error prone. The ETNT showed a trend for a slight median group improvement from 15 to 16 total located targets (+6%).

Conclusions: The high adherence rate and absence of adverse events showed that these exergames were feasible and safe for the participants. The results of the amount of exergames use is promising for future applications and warrants further investigations—for example, in the home setting of patients to augment training frequency and intensity. The preliminary results indicate the potential of these exergames to cause improvements in cognitive and spatial exploration skills over the course of training for stroke patients with VSN symptoms. Thus, these exergames are proposed as a motivating training tool to complement usual care. The ETNT showed to be a promising assessment for quantifying spatial exploration skills. However, further adaptations are needed, especially regarding calibration issues, before its use can be justified in a larger study sample.

(JMIR Serious Games 2017;5(3):e17) doi:10.2196/games.7923

KEYWORDS

exergames; eye tracking; virtual reality; visuospatial neglect; feasibility

Introduction

Unilateral spatial neglect (USN) is characterized by the inability to detect, respond, or orient toward stimuli presented on the contralateral side of a brain lesion [1]. Being a neurological disorder of attention, USN can affect the auditory, visual, or motor system [2-4]. With 43% in the acute phase and 17% at 3 months poststroke, USN is the most common and persistent problem associated with lesions of the right temporoparietal cortex [5]. Furthermore, USN patients share an unawareness of their deficits to different extents. This anosognopia, combined with an associated reduction in the ability to cope with activities of daily living [6], typically results in longer rehabilitation periods [7-10]. Therefore, USN is a predictor of poor outcome in stroke patients and an added burden for the health care system [7,8,11] requiring efficient treatment modalities [2,12-14].

A variety of accepted and proven traditional methods exist to treat USN [2,15-19], such as pharmacological interventions [20], different physiological sensory stimulations [21-23], and cognitive behavioral training [24]. A combination of multiple approaches to develop a personalized rehabilitation process is recommended [25,26] together with use of a battery of tests to assess USN rather than a single sole assessment [14,27]. However, none of these traditional methods could completely rehabilitate the condition, and rehabilitation methods investigating new approaches are warranted.

Virtual reality (VR), defined as "an advanced form of human-computer interface that allows the user to 'interact' with and become 'immersed' in a computer-generated environment in a naturalistic fashion" [28] shows some preliminary evidence favoring its use, and further investigations in stroke rehabilitation may complement traditional USN treatment methods [29-32]. VR methods provide a safe copy of the real environment while allowing the creation of customized rehabilitation programs through progressive, repetitive training with immediate feedback [13,19,26,33,34]. Promising VR instruments exist both for the assessment [35-39] and rehabilitation [30-32,40-44] of neglect [26]. The VR assessments were not only able to accurately detect USN patients but also made USN-related symptoms visible that were previously not identified with conventional assessments [26,33,34]. The VR systems tested for rehabilitation, however, were mostly complex to set up or used rather expensive tools (eg, head-mounted displays or cyber gloves), restricting their use to laboratory settings.

The European research consortium Rehabilitative Wayout in Responsive Home Environments (REWIRE) developed a nonimmersive VR system for stroke patients using portable devices with good performance and affordable equipment [45]. By creating such a VR system, REWIRE aimed to facilitate its use for stroke patients discharged from the hospital to allow continuation of the rehabilitation process within their own homes. A variety of home-based VR systems already exist for stroke patients mainly focusing on motor recovery [46-49], but none exist for USN. Therefore, the consortium designed, among others [50], exergames for the treatment of visuospatial neglect (VSN) (VSN being a subtype of USN [4]) [41,51]. Exergame is a portmanteau of the words exercise and game [52], allowing the patients to exercise their skills through gaming. In contrast to games that are designed for diversion for healthy persons, exergames should follow therapeutic principles—for example, the principles of exercise training, such as specificity and progression [53], or adopting the training method of shaping [54], including frequent feedback and the selection of tasks addressing the individual deficits of patients. The REWIRE consortium adopted the principles of exercise training as described by Hoffman [53] to design the neglect exergames. Therefore, the games include the principles of (1) specificity, implying that the required performance of each game corresponds to the goal of the game (to explore the neglected space) and (2) overload and progression, stating that the components being used must be exercised at a level the patient is not normally accustomed to and the patient should progress once accustomed to a level. In order to quantify training progression from simple to complex within each game, the REWIRE consortium used Gentile's taxonomy of motor skills as a template to develop the exergames (see Borghese et al [55] and Wüest et al [56] for more detail). Due to the nature of neglect and the related unawareness of neurological deficits [4], it is important to test such a novel intervention with the target patient population in a surrounding where close monitoring is possible and feasibility of the approach can be tested. Feasibility may cover aspects such as adherence, safety, and attrition to the novel intervention or whether the intervention and assessments all run smoothly [57].

Mainetti et al [41] and Sedda et al [32] already tested a former version of the REWIRE VSN exergames in a single-case study design involving a neglect patient in the chronic stage. The results were promising in terms of a positive attitude of the patient toward the exergames and in showing a trend for improvement of the VSN-related deficits in daily life. Based on the experience with the exergames of this single user together with feedback on their usability, the exergames were adapted and improved and then tested in this study for the first time in a case series of patients. We aimed to test the exergames in early stroke patients shortly before their discharge to home. This time point was chosen to include as realistic a target population as possible while still guaranteeing safety and supervision of the patients playing the exergames in the supportive environment of the rehabilitation clinic. Specific aims were to determine the feasibility of the exergames with minimal supervision in terms of (1) implementation of the intervention, including adherence, attrition, and safety, and (2) limited efficacy testing, aiming to document possible effects on VSN symptoms in patients early after stroke.

Methods

Study Design

We adopted a quasi-experimental pretest-posttest design with a subsequent follow-up to test the feasibility of the exergames in a case series of stroke patients with VSN symptoms. As we aimed to assess implementation of the exergames, thus testing if our intervention can be fully implemented as planned and proposed, an uncontrolled pretest-posttest design is appropriate [57]. A broad variety of definitions exist for the concept of case series in literature [58]. For our study, we used the definition of a case series as being a "report on a series of patients with an outcome of interest" [59]. Recruiting a small convenience sample was ideal for the planned limited efficacy testing, as we aimed to gain intermediate rather than final outcomes in this feasibility project, which allowed us to plan a shorter follow-up period [57].

Patients

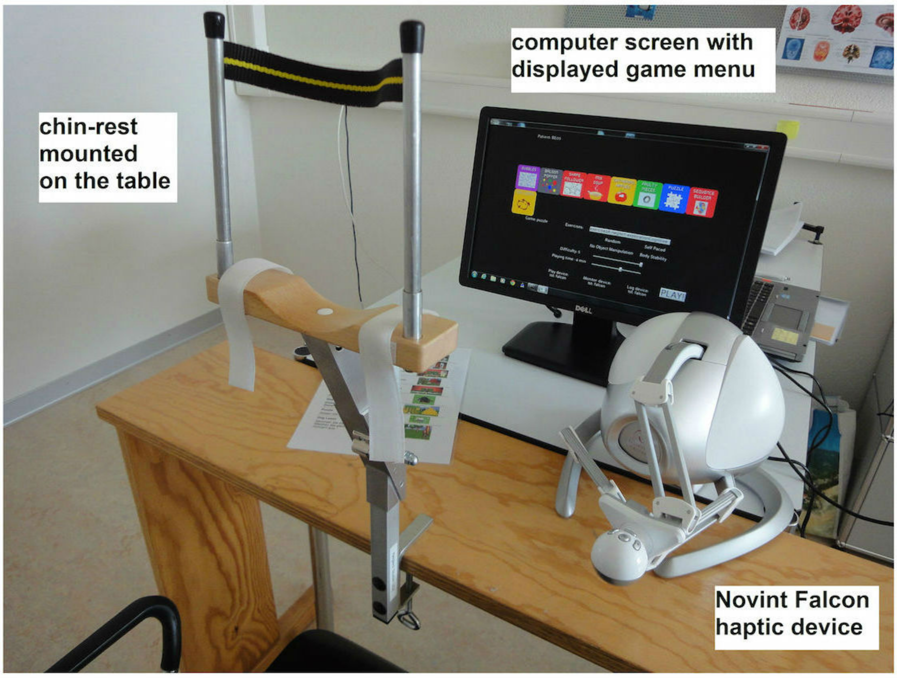
Identification of potential patients for this project was carried out by staff neuropsychologists and occupational therapists in 2 collaborating rehabilitation clinics (Klinik Bethesda Neurorehabilitation, Parkinson-Zentrum, Epileptologie, Tschugg, Bern, and Zürcher RehaZentrum Wald, Faltigberg-Wald, Zurich). They screened all incoming stroke patients with a diagnosis of VSN for eligibility in this study. We aimed for at least 5 participants, as this amount is considered the minimum reasonable number of independent subjects in a group to combine their data [58]. Fewer than 5 patients are usually presented in a descriptive, narrative form of individual case reports. We strived for a maximum of 10 patients as recommended by Abu-Zidan et al [58]. We included patients with a right brain lesion (RBL) due to a first stroke 15 to 180 days after the cerebral event and a diagnosed VSN as measured by the Catherine Bergego Scale (CBS) [60]. Inclusion criteria were being able to sit in a chair or wheelchair with a backrest for 45 minutes, being at least 18 years old, and having a clear view (with or without vision aids) of a computer screen placed at a distance of 60 to 65 centimeters from patient's face. VSN patients were excluded if their neglect was diagnosed as due to brain injury other than stroke, if severe apraxia was present—measured as less than 5 points on the Apraxia Screen of TULIA (test for upper limb apraxia) (AST) [61]—or if other noncontrolled medical conditions (eg, chronic pain, drug abuse) were present. Patients with a left brain lesion due to a first stroke were excluded because the exergame difficulty levels were designed to progress from the right (easy) to the left (difficult) side of the computer screen. An option to run the games vice-versa (from left to right) was not available.

All patients signed written informed consent before study entry. Ethical approval for the study was received from the local ethics committees (Zurich No. 2014-0543 and Bern No. 389/2014) as well as from the Swiss agency for the authorisation and supervision of therapeutic products (Swissmedic, 2015-MD-0003). The latter approval was required as the software was not yet certified with the European Community marking for medical devices. The study is registered at ClinicalTrials.gov [NCT02353962].

Setup

Patients were seated at a table in front of a 21-inch computer monitor at a distance of 60 to 65 cm in order to provide optimal eye tracking (Figure 1). We chose a seated position to allow more patients to participate (eg, wheelchair users) and avoid exhaustion through standing in an upright position. A height-adjustable chin rest (Novavision GmbH) was mounted on the table to avoid compensatory head movements while playing the exergames. Instead of a mouse to control games, a haptic Falcon Novint device (Novint Technologies) was used. This enabled individuals to experience a realistic sense of touch by providing simulated sensory feedback when reaching for and grasping virtual objects [62]. The Falcon Novint device can be handled with one hand only, allowing stroke patients to play the exergames with their nonaffected hand. The device was placed at the side of the computer monitor at a distance allowing ease of reach for the patients. The nonaffected upper extremity was positioned in approximately 45° shoulder abduction, 70° to 90° elbow flexion, and the forearm fully pronated. All participants were expected to independently complete 15 training sessions while being monitored by a supervising therapist. The supervision included observation of the patient during the intervention giving assistance where appropriate (eg, using the menu to start a new game). Observation was necessary for assistance if potential software difficulties occurred and for safety reasons for the patient, the latter being a regulation of the collaborating clinics.

Figure 1. Setup of the exergames training station.



Exergames

The intervention program consisted of a series of 9 exergames performed while seated. The games were designed to simulate real-world tasks, such as cooking from a recipe, going for a walk with a dog, or doing a puzzle (for detailed game information on 4 games, see Pirovano et al [51]). The Falcon Novint represented, for example, a dog leash by simulating a pull from the dog to the left or right side of a virtual walking path. The increase in difficulty of all games during the training course was accomplished according to Gentile's taxonomy of motor skills [56]. Using this systematic classification to design the exergames allowed us to design a theory-based rehabilitation program that followed the principles of exercise training (see Hoffman [53] and Ammann et al [63] for detailed descriptions of these principles). Playing time per game was adjusted from 1 to 10 minutes per game depending on the patient's ability to concentrate playing the VR game while maintaining a seated position. After initial training and instructions were given by the research team, all subsequent game adjustments during the intervention were performed by clinic staff (occupational therapists and neuropsychologists) in accordance with the patient's wishes.

Intervention Protocol

The VR-based VSN training intervention took place in the 2 collaborating rehabilitation clinics serving as an additional therapy option to the standard program, which comprised daily occupational, physical, and neuropsychological therapy. Each patient was asked to attend 5 30- to 45-minute sessions per week for 3 weeks. The supervising therapist individually adjusted the intensity of playing the exergames by changing the difficulty level or game duration in the game menu and by deciding if short breaks between each game would be necessary or not. In accordance with the training principle of individuality [53], which states that people respond differently to the same training stimulus, the patient selected 3 to 4 REWIRE VSN exergames from the game menu to be played in each session. The choice was based on personal interest of the patient, which was assumed to enhance motivation while playing. During the 3-week intervention time, patients were allowed to change games if they wanted to test another one or felt bored with the previously played game. After a break of 4 weeks, a follow-up measure was performed aiming to test the training principle of reversibility, which states that the ability to maintain performance is reduced when the training stimulus (the exergames) is removed.

Assessments

Primary Outcome

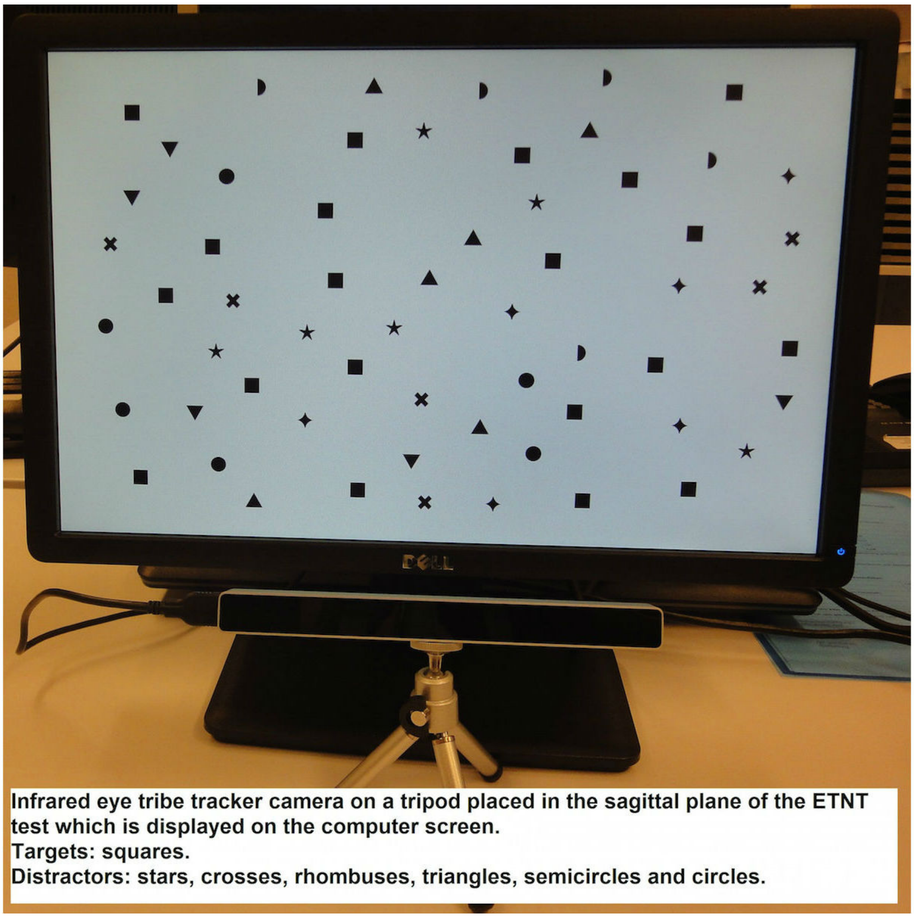
In order to measure the likelihood and extent to which our intervention can be fully implemented as planned and proposed [57], we designed a training diary as a protocol to document attrition, adherence, and safety issues. This training diary was on hand in the collaborating clinics and completed after each training session by the clinic staff in presence of the participating patient. The type of games played including difficulty level according to the Gentile's taxonomy, effective training time, and patient subjective statements regarding their perceived health condition after training (posed question: "How do you feel after training: fit or tired?") were all noted in the training protocol. Additionally, any adverse events related to the exergames intervention were noted. Potential adverse events could have been a recurrent stroke or other medical emergencies due to the early stage of recovery or an epileptic seizure or cybersickness due to playing the exergames [64]. For attrition, the number of participants lost during the intervention was registered. For adherence, participant engagement with the intervention was noted. We expected a good adherence to the intervention, defined as an attendance of at least 50% of the maximum 15 possible training sessions. Adherence was then calculated as the number of completed training sessions as a percentage of the maximum 15 possible training sessions.

Secondary Outcomes

Overview

In order to test limited efficacy of our intervention [57], the Eye Tracker Neglect Test (ETNT), Zürich Maxi Mental Status Inventory (ZüMAX), and Neglect Test (NET) were administered by the research staff at baseline and after the intervention. After a 1-month follow-up, the ZüMAX and NET were repeated either in one of the collaborating clinics or at the patient's (new) residence (home or retirement home), depending on the length of rehabilitation stay.

Figure 2. Setup of the Eye Tracker Neglect Test.



Spatial Exploration Skills

The ETNT is an adapted version of the cancellation test developed by Rabuffetti et al [34], aiming to assess symptoms of neglect. In contrast to the original test, in which targets are tagged by finger touch as measured by a touch screen, target detection is operated by eye fixation as measured by an eye tracker (Figure 2). The ETNT display consists of a uniform distribution of 60 stimuli including 20 targets (squares) and 40 distractors (other than square shapes) divided equally into 30 stimuli (10 targets, 20 distractors) on the right and left sides of the computer screen. The eye point of gaze was tracked with the Eye Tribe Tracker camera (Eye Tribe). Eye tracking is the process of using sensors to locate features of the eyes and estimate where someone is looking [65]. The technology relies on infrared illumination so that it does not interfere with the visual scenario. Since the system tracks eye movements relative to the sensor/screen, it is necessary to fix the head position, since head movements would be wrongly assumed as eye movements. Therefore, the patient's head was fixed on a chin rest. In our study, each participant was seated in front of the screen with the midsagittal plane of the trunk aligned with the center of the screen. An initial calibration of the Eye Tribe Tracker camera was then followed by 1 test trial with only 4 targets and 8 distractors and the ETNT with 60 stimuli. A stimulus was counted as being found (being circled) if the patient maintained his or her point of gaze for at least 0.4 seconds within an area surrounding the stimulus with a diameter of 7% of the total screen width, in keeping with Blignaut et al [66]. There was no time constraint; patients were instructed to inform the researcher when they had finished the test. This procedure was chosen to impose no stress on the patient while exploring the targets on the screen. However, if the patient got lost or became tired, the researcher present during the test asked the patient if he or she had the impression of having found all targets and then stopped the test depending on the patient's response.

The Neglect Test (NET) consists of 7 paper-and-pencil subtests (letter and star cancellation, copying 3 figures, and line crossing and bisection with a total possible score of 70 points) and 10 behavioral subtests (representational drawing, scanning 3 pictures, menu and article reading, telling time, setting time on a digital and analog watch, and address copying with a total possible score of 100 points) designed to identify a wide variety of visual neglect behaviors [67]. It has been shown to be a robust predictor of VSN and is a predictor of functionality after stroke [68]. To assess the level of anosognosia for VSN after stroke, self-ratings of performance in 6 subtests of the NET (figure copying, star cancellation, line crossing and bisection, representational drawing, and article reading) were contrasted with external performance ratings of the examiner on a 5-point Likert scale (ranging from 1=severe difficulties to 5=no difficulties). The degree of unawareness for VSN was quantified as proposed by Vossel et al [69] (see Figure 3).

This anosognosia index (AI) will be smaller than 0 if the patient suffers from anosognosia, indicating an overestimated self-performance to what objectively has been performed. If the patient is able to rate his or her performance realistically, thus being below or matching the external rating, the index becomes equal to or greater than 0, indicating no signs of anosognosia.

Figure 3. Formula for anosognosia index.

$$\text{Anosognosia index} = \frac{\sum \text{external rating} - \sum \text{self-rating}}{\sum \text{external rating}}$$

Cognitive Skills

The ZüMAX is a domain-specific assessment tool measuring cognitive impairment by evaluating executive function, language, praxia, visual perception and construction, and learning and memory (see Tobler-Ammann et al [70] for a detailed description of the test). Each of the 5 domains allows a maximum score of 6 points, with a maximum possible test score of 30 points, representing optimal cognitive functioning. The ZüMAX has moderate to good test-retest reliability for the total test scores in patients 6 months or more poststroke and may discriminate between this patient group and healthy age and gender matched persons [70]. The ZüMAX visual perception and construction domain is the one indicating VSN symptoms. The task for visual perception is to recognize and name degraded figures, unfamiliar scenes, and a face. The task for visual construction consists of copying a figure. This assessment was chosen due to its advantage of providing both general information about poststroke cognitive impairment and neglect-specific information and because of its origin in Switzerland where the study took place and, therefore, matching the cultural background of the participants.

Data Analysis

Data analysis was carried out using SPSS for Windows version 23.0 (IBM Corp). A Shapiro-Wilk test was administered and quantile-quantile plots were drawn to test normality of the data. The results confirmed our assumption of nonnormally distributed data due to the small sample size ($P \leq .05$ for most parameters). We therefore used nonparametric tests for data analysis. Accordingly, a Wilcoxon signed rank test was adopted to compare post- with preintervention results and follow-up with postintervention results. The Friedman test was used to test for differences in the NET and ZüMAX between all 3 measurement time points [71]. We analyzed the data for each individual and for the whole group. The fact that the ZüMAX and NET comprise subtests and the NET additionally provides a conversion table to transform raw scores into standard scores allowed us to use the Wilcoxon signed rank test not only on a group level but also on an individual level. For calculations per patient, we used the achieved standard scores of each subtest as variables, resulting in 17 variables (corresponding to the 17 NET subtests) for the NET and 5 variables (corresponding to the 5 ZüMAX domains) for the ZüMAX. For the analysis on a group level, we compared the achieved total scores per measurement point of the 7 patients.

The ETNT data were provided by the software described in Rabuffetti and colleagues [34]. A subset of the relevant indexes—namely those that were related to visual perception—was used for data analysis as only these items were suitable for the adapted test version. As the ETNT software provided 1 value per index and patient, we used the Wilcoxon signed rank test to analyze post- to preintervention changes within the sample. Additionally, we graphically displayed the individual changes post-pre intervention by drawing the performed search path and fixation points and creating heat maps to visualize group changes post-pre intervention.

In order to perform an a priori power analysis to determine the minimum sample size for a future randomized controlled trial, we calculated the effect sizes for the secondary outcome measures. We applied the Cohen formula for nonparametric tests [72] (see Figure 4). Accordingly, small, medium, and large effect sizes were labeled as r=0.1, 0.3, and 0.5, respectively [73]. The level of significance was set at $P \leq .05$.

Figure 4. Cohen formula for nonparametric tests.

$$\left(r = \frac{Z}{\sqrt{n}}, \text{ where n is the number of pairs and Z being the converted U score}\right)$$

Results

Overview

From the 18 VSN patients consecutively screened for eligibility in both clinics from March 2015 to March 2016, 7 patients (39%) were eligible and consented to participate in this study, therefore taking part in the VR exergaming program including baseline, postintervention, and 3-month follow-up measures. Reasons preventing patients from participating were suffering from a right-sided VSN due to a left brain lesion, having a severe apraxia (fewer than 5 points on the TULIA (AST) screening instrument, and being in a poor health condition confining them to bed. Patient characteristics are presented in Table 1.

Table 1. Patient characteristics.

Patient		Age, years	Sex	Days post-stroke at study entry	RBL[a] stroke type	Handedness/ affected hand (function)	Education	Locomotion	CBS[b,i]	AST[c,j]
P1		64	M	25	ischemia	R/L (none)	PE[d]	WC[e]	7	12
P2		74	M	29	ischemia	R/L (back)	PE	W[f]	17	12
P3		64	M	114	ischemia	R/L (none)	PE	WC	5	12
P4		70	M	32	ischemia	R/L (back)	SE[g]	WC	6	12
P5		53	M	42	ischemia	R/L (none)	PE	W	5	12
P6		78	F	35	hemorrhage	R/L (back)	SE	W	10	12
P7		77	F	47	hemorrhage	R/L (back)	PE	WC	16	9
IQR[h]										
	25	64	—	29	—	—	—	—	5	12
	50	70	—	35	—	—	—	—	7	12
	75	77	—	47	—	—	—	—	16	12

[a]RBL: right brain lesion.
[b]CBS: Catherine-Bergego Scale.
[c]AST: Apraxia Screen of TULIA.
[d]PE: primary education.
[e]WC: wheelchair.
[f]W: walker.
[g]SE: secondary education.
[h]IQR: interquartile range.
[i]Maximum score = 30 (severe neglect); 0 points = no neglect.
[j]Maximum score = 12 (no apraxia); threshold for apraxia: 9 points; severe apraxia: 5 points.

Primary Outcome

An overview of individual (P1-P7) and group (interquartile range [IQR], mean) results in the training protocol is shown in Multimedia Appendix 1. There were no adverse events and drop-outs during the intervention. A median attendance of 14 (IQR 12-15) training sessions (maximum 15 sessions) was achieved, which corresponds to a median adherence of 93% (IQR 80%-100%). Reasons for nonparticipation were of organizational or medical nature (eg, overlap with other therapy sessions or due to fatigue) rather than because of motivational factors. All patients played 2 to 4 games and repeated at least 1 game per training session. The supervising therapists adapted and individually progressed the patient training protocols on a weekly basis during the exergames intervention in accordance with patient progress. If, for example, the patient got bored with the current difficulty level of the played game or the therapist observed that the game was played without effort, the therapist modified the difficulty level within each game. However, if the patient had reached the most difficult level, the therapist replaced easy games with more complex ones (ie, games including more distractors or moving objects). An analysis of the progress as measured by the achieved game scores was therefore not feasible, as progression in difficulty resulted in a temporary decrease in game scores. Instead, the progress in the exergames training of the 7 individual patients was documented weekly according to the Gentile’s taxonomy of motor skills. These results are shown in Multimedia Appendix 1.

Secondary Outcomes

Spatial Exploration and Cognitive Skills

An overview of the individual ETNT scores and group changes post- to preintervention is shown in Multimedia Appendix 2. Figure 5 shows 2 examples of pre-post intervention search path strategies and fixation points as measured by the eye tracker camera (see Multimedia Appendices 3 and 4 for all graphs of individual post-pre ETNT search paths and fixation points). Figure 6 shows the heat maps of the pre- and postintervention and differences in post-pre detected targets of the ETNT. An overview of ZüMAX, NET, and AI scores and group changes pre-, postintervention, and at follow-up is summarized in Multimedia Appendix 5 and graphically displayed in Figure 7 (overview) and Multimedia Appendix 6 (individual results per outcome measurement). The individual changes in the ZüMAX and NET assessments are presented in Multimedia Appendix 7.

Figure 5. Examples of pre- and postintervention results of the Eye Tracker Neglect Test search paths and fixation points of P3 and P4.

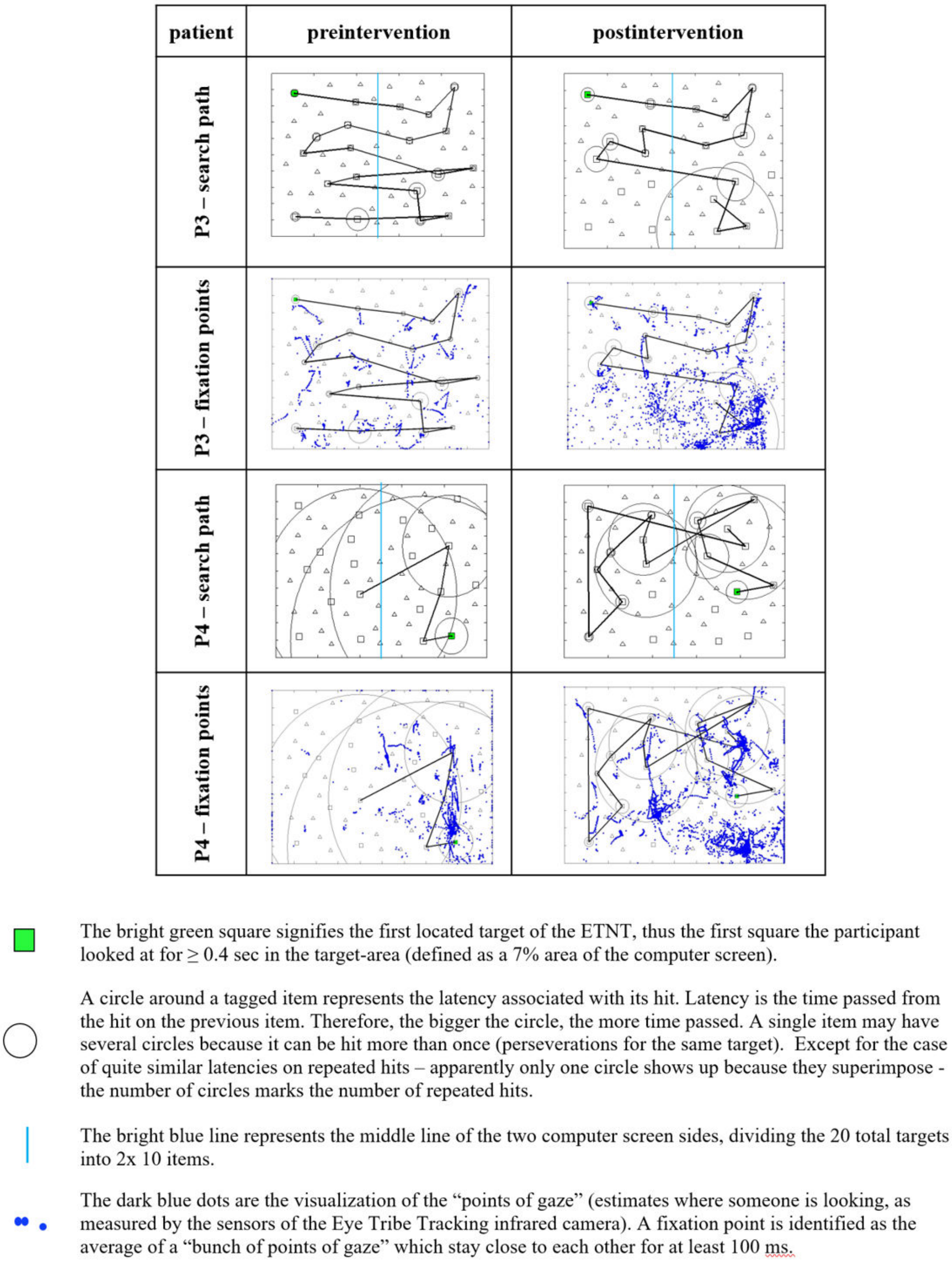


Figure 6. Heat maps of the preintervention, postintervention, and difference post-pre results of the Eye Tracker Neglect Test.

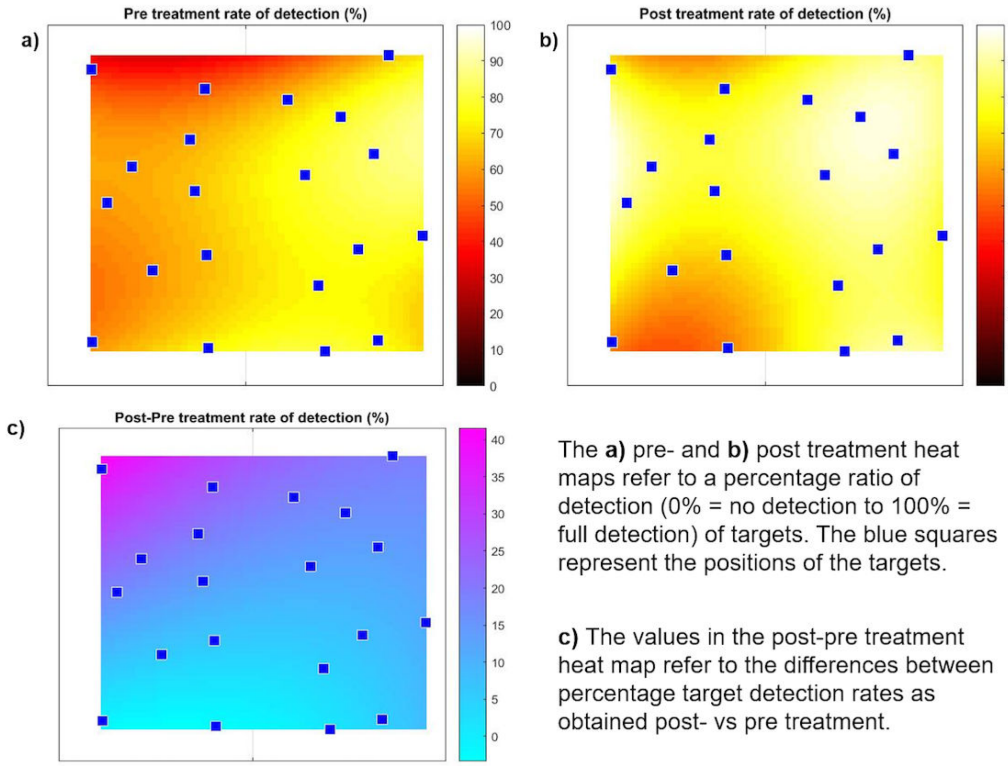
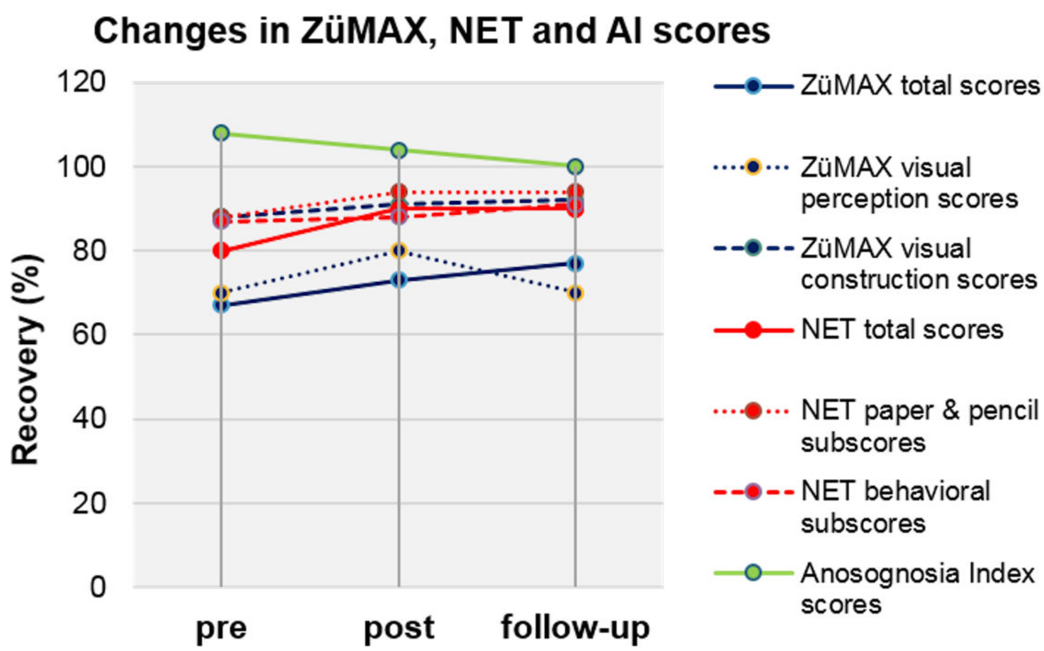


Figure 7. Graphical overview of preintervention, postintervention, and follow-up Zürich Maxi Mental Status Inventory, Neglect Test, and anosognosia index results.



Eye Tracker Neglect Test

Group Level

The pre-post assessment showed a median group trend of slight improvement in the total located targets from 15 to 16 (+6%) pre-post, which was concomitant with an increasing median total test duration (+33.9 seconds pre-post) (Multimedia Appendix 2). The postintervention performance showed a median decline of 2 (IQR 0-4) missed targets on the left side of the screen and a median increase of 1 (IQR 0-3) missed target on the right side of the screen. The heat maps (Figure 6) indicate that the ability to detect targets in the upper left portion of the computer screen increased postintervention and remained substantially unmodified otherwise. The results further showed an unchanged median group trend pre-post intervention regarding the neglect score, the median latency, and proximity. There were no statistically significant changes pre-post intervention for any ETNT parameters (Multimedia Appendix 2).

Individual Level

P4 improved from 5 to 15 total located targets pre-post intervention (Multimedia Appendix 2 and Figure 5). The only individual worsening pre-post regarding the left spatial exploration skill was P3, with no target missed preintervention and 4 targets missed postintervention (Figure 5). Most participants (6/7, 86%) started their search in the right sector and scanned leftwards vertically (Multimedia Appendices 3 and 4), while P3 started in the upper left sector and scanned top-down horizontally (Figure 5). Additionally, 4 out of 7 (57%) started their search on the right side of the screen, 2 out of 7 (29%) were able to change the starting point from right to left, and 1 participant (P3) started the search on the left side of the screen pre- and postintervention (Multimedia Appendices 3 and 4).

Neglect Test

Group Level

The NET showed statistically significant improvements pre- to postintervention (*P*=.01 to *P*=.03) in the total score and both subtests as well as in the Friedman test (*P*=.01 to *P*=.02) (Multimedia Appendix 5). The AI results showed a group trend toward zero (median 0.08 pre, 0.04 post, 0 follow-up), indicating a trend toward perfect awareness of oneself (Multimedia Appendix 5).

Individual Level

P1 and P2 declined at follow-up in the NET total scores, while P3 to P7 showed further improvement. P1, P5, and P7 significantly changed in their NET total scores, P1 post–follow-up (*P*=.04) and P5 and P7 pre-post–follow-up (Friedman test; *P*=.01 and *P*<.001, respectively) (Multimedia Appendix 7). The post–follow-up result of P1 also showed a large effect (*r*=–.80), indicating a large decline in the NET scores postintervention, especially in the paper-and-pencil subtasks (Multimedia Appendix 6). Analyzing NET scores by subtests, all patients improved pre- and postintervention in the paper-and-pencil subtests (Figure 7), while in the behavioral subtests, all patients improved pre- to postintervention except for P3 who remained unchanged (Multimedia Appendix 6). Two patients (P3 and P7) suffered from anosognosia with a trend of aggravation from pre- to follow-up assessments (Figure 7). P1, P2, and P4 showed no signs of anosognosia at follow-up (AI index=0), while P5 and P6 showed a trend toward an increasing AI index, underestimating their actual performance (Multimedia Appendix 6).

Zürich Maxi Mental Status Inventory

Group Level

The ZüMAX showed improvements in the total scores from pre- to postintervention to follow-up (Figure 7) that were not statistically significant (*P*=.29 to *P*=.45, median +2 points pre-post, +1 point post–follow-up) (Multimedia Appendix 5).

Individual Level

On an individual level, P1, 2, 5, and 6 improved from pre- to postintervention in the ZüMAX total scores, while P3 and 4 declined and P7 remained unchanged (Multimedia Appendix 6). The post–follow-up scores declined in P1 and P7, while P2 to P6 still improved their post–follow-up scores, with P3 and P4 declining pre-post intervention. In the ZüMAX visual perception subtask (recognizing and naming degraded figures), 3 of the 7 patients stayed unchanged from pre-post to follow-up (P3, P5, P6), while the largest progression was apparent in P7, with a clear decline of 3 points after termination of the exergames intervention (Multimedia Appendix 6). In the second ZüMAX subtask related to neglect (visual construction: figure copying), 3 patients performed the pre- and postintervention assessments with unchanged scores (P3, P6, P7), and 3 patients showed a slight decline post–follow-up (P1, P3, P5).

Discussion

Principal Findings

This study evaluated the feasibility of an exergames intervention aimed to affect VSN symptoms in patients early poststroke in terms of implementation (adherence, attrition, and safety) and limited efficacy testing by documenting changes in VSN symptoms. The exergames intervention was tolerated well by all participants and was mainly performed without major difficulties, showing that its implementation in the clinical setting was feasible. With 0 out of 7 (0%) attrition, no adverse events, and a median adherence rate of 14 out of 15 sessions (93%), the compliance of the patients to the exergames was excellent. Such a result was possibly due to the clinic staff's commitment, as the VR intervention was smoothly integrated into the daily therapy schedule of the clinic. However, as we aimed to test the fit of our intervention in a real-world setting, we prioritized clinic constraints over optimal conditions and settings. As a consequence, this priority reduced potential omissions of training sessions as described in purely home-based VR interventions [46]. There, the level of use of the VR system was variable and fell far short of recommendations, despite the weekly or biweekly visits of a researcher to the patients' homes to check progress and retrieve data.

Other studies testing novel VR systems for upper limb stroke rehabilitation have also shown high levels of adherence to the training intervention [74-76]. However, these patients were in the chronic stage of recovery and did not suffer from USN. The single participant with USN of the Duckneglect study (Mainetti et al [41]), who also was in the chronic stage of stroke recovery, showed an excellent adherence to the exergames, in keeping with our case series.

Regarding the exergames training, the median duration per session was 30 (IQR 23-30) minutes, which fell short of the planned 30 to 45 minutes of training time. For our study, we decided to set a timeframe rather than an exact exposure time, because little is known about the optimum duration and patterning of training exposure to virtual environments [77]. Possible reasons for the rather short training sessions in our sample were twofold: either patients (eg, P2 and P3) were quite fit and finished the planned exergames session early or, conversely, were too tired to play longer (eg, P1). In our sample, 5 out of 7 (71%) patients indicated being fit after most trainings (median 13 out of 15 [87%] possible sessions), excluding fatigue as being a main reason for the rather short training time. P7, however, being the only participant with a highly distinctive VSN as measured with the NET, needed on average 34 minutes to accomplish the games. These results highlight the importance of adjustability of the difficulty level of the exergames to the functional ability of the stroke patient [76], thus avoiding a decline in enjoyment level while playing [77]. Given the uncertainty about optimal exposure together with our small and highly varied sample (Table 1, CBS scores), future trials should focus on investigating optimal thresholds of exposure time corresponding to the degree of VSN severity.

The fact that there were no adverse events during the training period in our case series was encouraging. Besides being lucky that no recurrent stroke or other medical emergency happened during the intervention, the design of the games might have contributed as well to the safety of our participants. For example, implementing both stationary and in-motion conditions of the virtual scenario together with the option of choosing between intertrial variability and no intertrial variability while gaming allowed the patient to choose the optimal virtual environment to be challenged on the one hand but not be overwhelmed on the other hand (see Multimedia Appendix 1). Allocating these options in difficulty level might have contributed to reducing the risk of cybersickness while playing despite the stationary condition of the patient [64]. When designing the setup of our study, we intentionally planned a seated position to play the games. This allowed patients to fully concentrate on the exploration of the neglected space without having to invest energy standing in an upright position. Furthermore, playing the games in a seated position contributed to the prevention of falls. Prahm et al [78], for example, also designed a game-based intervention in a seated position reporting no adverse events. However, their participants were able-bodied adults. Wiloth et al [79] reported no adverse events in their game-based assessment to measure motor-cognitive function in people with dementia while they were standing on a movable platform. Although falls are highly prevalent in people with cognitive impairment such as dementia [80], people poststroke additionally suffer from motor impairment. Despite their hemiparesis, our participants were all able to perform the games and handle the Falcon Novint with the nonaffected hand. The clinic staff reported that sometimes the more concentrated or—toward the end of the training session—the more tired the participants became while playing the exergames, the more they tilted to the left side with their upper body. As this is a well-known phenomenon in VSN patients poststroke [81], we think our approach of offering gameplay in a seated position guaranteed patient safety. The rather tilted position, however, did not prevent the participants from continuing to play the exergames.

Our limited efficacy testing showed a group trend of improvements in cognitive and spatial exploration skills. However, these changes cannot be exclusively attributed to the exergames intervention. One reason is the ongoing VSN treatment in the rehabilitation clinic that might also explain some of the improvements. A further possible reason is spontaneous recovery of VSN symptoms not only during the acute phase after stroke but also during the following few weeks. Paolucci et al [82], for example, reported a decrease of VSN symptoms to 20% from 45% after 1 month poststroke, which may also have occurred in our sample. Additionally, the heterogeneity in our sample regarding neglect severity—4 out of 7 (57%) were only mildly affected with CBS scores between 5 to 7 points (Table 1), while 2 out of 7 (29%) were severely affected (16-17 scores on the CBS)—might have influenced the rate of improvements, too. However, our sample did not show a ceiling effect—being present if 15% or more participants achieve the highest possible score [83]—as no participant achieved the highest score in any of the outcome measurements. Furthermore, most patients continued improving their scores in the NET and ZüMAX assessments postintervention, achieving the highest scores after a break of 4 weeks (follow-up). Only P1 in both tests and P2 (NET) and P7 (ZüMAX) showed a decline in scores from post to follow-up, which would correspond to the training principle of reversibility [53,63] that states that once a training stimulus is removed, performance levels will eventually return to or below baseline. Comparing our efficacy testing results with literature was difficult, as studies with a similar setup, time point of measurement, and target group are scarce. There is evidence that training with VR methods improve spatial attention and show transfer of improved spatial attention in activities of daily living in chronic neglect [30,32]. Kim et al [84] showed additional benefit for treating cognitive impairment in stroke patients without VSN in the subacute phase of recovery when adding VR training to classical cognitive rehabilitation. The evidence supports our findings that using VR systems to treat cognition in stroke patients is promising and feasible; however, further research is warranted and necessary to test its use in patients with VSN symptoms early poststroke. Future studies with a focus on treatment effects using controlled research designs should be used to assess causal relationships between the game-based interventions and important patient outcomes.

The median AI values in our sample ranged from 0.08 preintervention to 0.0 at follow-up. Comparing those results to bigger RBL stroke samples with USN—mean (SD) lower AI –0.28 (0.5) for n=34 and mean (SD) higher AI –0.47 (0.5) for n=22; Vossel et al [69] and mean (SD) AI –0.16 (0.38) for n=55; Vossel et al [6]—our 7 patients showed quite a high level of self-awareness for their visuospatial deficits, including P3 and P7 who scored below zero (indicating anosognosia) during all 3 measurements. Of the 7 patients, 3 continued increasing their level of self-awareness postintervention to zero (P1, P2, P4), suggesting positive effects of time poststroke on anosognosia rather than our training intervention. However, time poststroke might not be a viable indicator for those continued improvements in self-awareness of neglect, as Vossel and colleagues [6] found no differences in their AI values across their 3 patient subgroups differing in time since stroke onset. Therefore, continued rehabilitation might be a plausible reason for those further improvements. However, looking at the other 4 patients, AI values showed a tendency toward worsening from preintervention to follow-up, with P3 and P7 overestimating and P5 and P6 underestimating their NET performance, although they also had continued rehabilitation. There is evidence that anosognosia for spatial deficits is not predominant, with different tasks evoking different degrees of awareness about the neglect symptoms [85]. As the AI is calculated on the basis of 4 paper-and-pencil and 2 behavioral tasks of the NET, it might be that this mix of tasks also influenced the miscellaneous AI results. For example, Ronchi et al [85] found that anosognosia level improved after performance of complex visuomotor (eg, cancellation and drawing) and reading tests. By contrast, the self-rating in line bisection tasks was not related to actual task performance [85]. Furthermore, as the AI test is designed to be performed after task execution, it might be that the patients were able to correct their erroneous self-rating to some extent at least in the complex visuomotor tasks. Last but not least, the repetition of the NET test over a relatively short time span might have influenced the AI results, too, as the patients knew that a self-rating would follow after certain tasks.

The ETNT results are to be considered preliminary and should be interpreted with caution. Calibration difficulties with the Eye Tribe Tracker system (eg, most patients only reached 3 out of 5 points in calibration quality scores) may have influenced the reliability of the setup and the accuracy of the results. The calibration consisted of eye-tracking a circle that moved around the whole display. The difficulties experienced by patients in following the rapidly moving circle and the requirement to look at calibration points at the very left of the computer screen were the main reasons for the rather poor calibration results. Such difficulties may produce visible effects (in Figure 5, for example, P4 evidences a dense cloud of gaze points on the bottom right corner during the postintervention assessment, where P4 unsuccessfully tried to tag the 3 targets he could point at with his hand). Baheux et al [86] also reported calibration problems with their 3-D haptic VR system coupled with an eye-tracking device. They assumed that the VSN patient spectacle wear or eye color might have been reasons for calibration difficulties. However, these calibration difficulties notwithstanding, our ETNT results showed trends toward slight improvements in both total located and missed targets on the left side of the screen. The heat maps display the increased ability to detect targets in the upper left portion of the computer screen postintervention but remained substantially unmodified otherwise. However, the preintervention performance was already fairly good in our sample. Furthermore, the heat maps show that the ETNT can identify neglected areas. This is in line with the Rehabilitation Gaming System by Maier et al [31] using the Kinect motion capture system being equally able to measure symptoms of neglect. In contrast to our test, the stroke patients in the chronic stage of recovery explored the neglected side with the paretic arm.

The individual search strategy (Multimedia Appendices 3 and 4) of most patients was comparable with those described by Müri et al [65] and Rabuffetti et al [34], namely to start in the (extreme) right sector and scan leftwards vertically. This contrasts with the search strategy demonstrated by the control subjects in these studies, which started in the upper left sector and scanned top-down horizontally (like reading). Only P3 showed a nonneglect-specific search strategy (Figure 5). The 4 missed targets in the left lower corner postintervention, which P3 was able to detect preintervention, were due to calibration difficulties, as P3 was able to point at those 4 targets with his hand. P1 and P6 were the only patients able to shift their search starting points from the right to the left side from pre- to postintervention, indicating improvements in exploring the neglected side [34]. Not surprisingly, the increased total test duration pre- to postintervention in our sample went along with slightly more detected targets. When the participant increases the number of detected targets, it can be the case that previously neglected targets are now detected albeit with a fairly large latency. We interpret this as positive since more visual space is actively explored but latency and concomitantly the total test duration may therefore also increase. A future study including a larger sample and a control condition is, however, warranted to substantiate or refute these findings.

We performed an a priori power analysis to determine the minimum sample size for such a future trial [87]. Specifically, we assessed the requirements for a randomized controlled study with an experimental group (receiving exergame-based therapy and usual stroke rehabilitation) and a control group (receiving usual stroke rehabilitation only). Assuming an effect size of r=0.9 (based on our observed value for NET total scores, Multimedia Appendix 5), acceptable type I and II error probabilities (0.05 and 0.20, respectively) may be obtained with a minimum sample of 34 subjects per group for a 2-group pre-post-test design. To account for attrition, initial sample size should be increased to 45 subjects per group [88]. Given the fact that only 18 potential participants were available within 12 months of recruitment, we recommend collaborating with more than 2 clinics for such a trial.

Limitations and Future Work

The length of the training phase was rather short (ie, 3 weeks). We deliberately did not choose a longer training period, as we primarily wanted to test the exergames' feasibility and not their effect on VSN symptoms. On the other hand, the rather short training phase allowed us to keep the drop-out risk relatively low (eg, due to discharge home during the training phase). In a next step, it would be important to test the exergame system's feasibility in patient homes to evaluate adherence, safety, and attrition to using the system in this setting, as the provision of novel home-based rehabilitation options was the main goal of REWIRE. In this setting, a longer training phase could be tested. Furthermore, a progression as measured by the game scores should be implemented together with an immediate graphical feedback after each training session to enhance motivation for playing the exergames. For this implementation, ideas from the rehabilitation method of shaping [54], where frequent feedback and encouragement during training are central, could be adopted. In order to maximize confidence that changes in outcomes can be attributed causally to the exergames intervention, a control group in a pilot randomized controlled trial design would be needed. The neglect exergames should further be designed to switch levels of difficulty (ie, progressing from the right to the left side of the screen or vice-versa). Designing this option would allow recruiting stroke patients with a left-sided brain lesion and VSN symptoms, too. By excluding them in our project we were aware that we would probably miss some patients having ipsilesional neglect [89], which would have made a participation in the exergames intervention feasible. However, as left-sided neglect is quite rare compared to right-sided neglect [5], the risk of missing such an ipsilesional neglect patient was relatively low.

The ETNT could further be developed regarding the following:

- Calibration procedure of the Eye Tribe Tracker by reducing the speed of the circle to be followed, for example
- Software indexes, which were initially designed for the touchscreen (hand-eye coordination) test. Indexes important for eye-tracking would be, for example, the cumulative fixation duration, spatial distribution of fixations in the horizontal and vertical plane, or the number and amplitude of exploratory saccades as explored by Müri et al [65]
- Collection of the search strategy patterns of age-matched controls

Additionally, future work could correlate ETNT measures to scores in standardized clinical scales, such as the NET scores, in order to validate the derived ETNT measures of recovery after VSN.

Conclusion

This study showed that patients adhered well to the REWIRE neglect exergames intervention with no drop-outs, no adverse events, and an adherence rate of 14 out of 15 sessions (93%). We therefore judged this intervention to be safe and feasible for VSN patients early poststroke and appropriate for further testing. Cognitive and spatial exploration skills, as evaluated using ETNT, NET (spatial exploration), and ZüMAX (cognition) assessments, improved in most patients from pre- to postintervention. The results of the amount of exergames use is promising for future applications and warrants further investigations, for example, in the home setting of patients as a motivating training tool to complement usual care and support augmenting training frequency and intensity in RBL stroke patients with VSN.

Acknowledgments

BCT-A designed the study; provided support in designing the exergames; conducted the acquisition, analysis, and interpretation of the data; and wrote the manuscript. EF and MR developed the software and exergames and contributed to the analysis and interpretation of data and writing of the manuscript. LW helped recruit the patients and edited the manuscript. EDdB, NAB, and RHK initiated the study and contributed to design, writing, and editing of the manuscript. All authors read and approved the final manuscript.

This work was partially supported by the REWIRE project (www.rewire-project.eu) and funded by the European Commission under the FP7 framework with contract 287713 and the Occupational Therapy Association of Switzerland. Author MR was supported by funding (Ricerca Corrente) from the Italian Ministry of Health.

Many thanks go to the collaborating clinics who made the patients recruitment possible, namely to Klaus Meyer, MD, Klinik Bethesda, Tschugg, Canton of Berne, Switzerland, and his team of neuropsychologists and to Andreas Sturzenegger, MD, Klinik Wald, Wald, Canton of Zurich, Switzerland, and his team of occupational therapists. Laura Wiederkehr, former master student of the ETH Zurich, is very much appreciated for her scientific and administrative support and for performing the measurements. Further thanks goes to Gabriel Baud Bovy (Istituto Italiano di Tecnologia, Genova) for his work on the Novint Falcon haptic device. Finally, many thanks to Martin J Watson, PhD, for proofreading the manuscript for English and structure.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Overview of individual and group results in the training protocol.

[PDF File (Adobe PDF File), 33KB - games_v5i3e17_app1.pdf]

Multimedia Appendix 2

Overview of individual Eye Tracker Neglect Test scores and group changes pre- to postintervention.

[PDF File (Adobe PDF File), 45KB - games_v5i3e17_app2.pdf]

Multimedia Appendix 3

Pre- and postintervention results of individual Eye Tracker Neglect Test search paths.

[PNG File, 432KB - games_v5i3e17_app3.png]

Multimedia Appendix 4

Pre- and postintervention results of individual Eye Tracker Neglect Test fixation points.

[PNG File, 710KB - games_v5i3e17_app4.png]

Multimedia Appendix 5

Overview of Zürich Maxi Mental Status Inventory, Neglect Test, and anosognosia index scores and group changes preintervention, postintervention, and follow-up.

[PDF File (Adobe PDF File), 40KB - games_v5i3e17_app5.pdf]

Multimedia Appendix 6

Graphical display of individual Zürich Maxi Mental Status Inventory, Neglect Test, and anosognosia index scores.

[PNG File, 324KB - games_v5i3e17_app6.png]

Multimedia Appendix 7

Individual changes in the Zürich Maxi Mental Status Inventory and Neglect Test assessments.

[PDF File (Adobe PDF File), 42KB - games_v5i3e17_app7.pdf]

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Abbreviations

AI: anosognosia index
AST: Apraxia Screen of TULIA
CBS: Catherine Bergego Scale
ETNT: Eye Tracker Neglect Test
IQR: interquartile range
NET: Neglect Test
RBL: right brain lesion
REWIRE: Rehabilitative Wayout in Responsive Home Environments
TULIA: test of upper limb apraxia
USN: unilateral spatial neglect
VR: virtual reality
VSN: visuospatial neglect
ZüMAX: Zürich Maxi Mental Status Inventory

Edited by G Eysenbach; submitted 26.04.17; peer-reviewed by P Standen, B Ballester, N Skjaeret; comments to author 31.05.17; revised version received 13.07.17; accepted 31.07.17; published 25.08.17.

Please cite as:
Tobler-Ammann BC, Surer E, de Bruin ED, Rabuffetti M, Borghese NA, Mainetti R, Pirovano M, Wittwer L, Knols RH
Exergames Encouraging Exploration of Hemineglected Space in Stroke Patients With Visuospatial Neglect: A Feasibility Study
JMIR Serious Games 2017;5(3):e17
URL: http://games.jmir.org/2017/3/e17/
doi:10.2196/games.7923
PMID:28842388

Original Paper

User Perspectives on Exergames Designed to Explore the Hemineglected Space for Stroke Patients With Visuospatial Neglect: Usability Study

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Abstract

Background: Visuospatial neglect due to stroke is characterized by the inability to perceive stimuli emerging in the area opposite to the side of brain damage. Besides adopting conventional rehabilitation methods to treat neglect symptoms, the use of virtual reality (VR) is becoming increasingly popular. We designed a series of 9 exergames aimed to improve exploration of the neglected side of space. When new VR interventions are designed, it is important to assess the usability aspects of such management strategies within the target population. To date, most studies used questionnaires to assess user satisfaction with the intervention or product being tested. However, only a combination of both quantitative and qualitative data allows a full picture of user perspective.

Objective: The purpose of this study was to quantitatively and qualitatively assess patient and therapist perspectives of a VR intervention based on the series of 9 exergames designed to explore hemineglected space. Specifically, we wanted to evaluate (1) perceived-user friendliness of the exergames, (2) attitude towards using the exergames, and (3) intention to use the exergames in the future.

Methods: A total of 19 participants (7 patients, 12 therapists) evaluated the exergames they had used 5 times a week during 3 weeks. The Technology Acceptance Model (TAM) questionnaire was filled out after the intervention. Based on those responses, we conducted focus group interviews (with therapists) and individual interviews (with patients). To analyze the TAM questionnaires, we used descriptive statistics. We adopted content and comparative analysis to analyze the interviews and drew illustration maps to analyze the focus group interviews.

Results: The therapists took a more critical stance with a mean TAM questionnaire total score of 48.6 (SD 4.5) compared to the patients who had a mean total score of 56.1 (SD 12.3). The perceived user-friendliness score was 5.6 (SD 1.4) for patients and 4.9 (SD 1.4) for therapists. The attitude towards using the exergames was rated 4.8 (SD 1.9) by patients and 3.6 (SD 1.4) by therapists, respectively. The intention to use the exergames in the future was rated 3.9 (SD 2.1) by patients and 3.7 (SD 1.8) by therapists. We gained information on how to improve the exergames in the interviews.

Conclusions: Patients and therapists perceived the exergames as user-friendly; however, using the games further with the actual test version was not perceived as conceivable. The therapists were generally more critical towards future use than the patients. Therefore, involving both users to achieve acceptable and user-friendly versions of game-based rehabilitation for the future is deemed crucial and warranted.

Trial Registration: Clinicaltrials.gov NCT02353962; https://clinicaltrials.gov/ct2/show/NCT02353962 (Archived by WebCite at http://www.webcitation.org/6soxIJlAZ)

(JMIR Serious Games 2017;5(3):e18) doi:10.2196/games.8013

KEYWORDS

usability; user perspective; mixed-methods; exergames; visuo-spatial neglect; stroke

Introduction

Stroke-related visuospatial neglect (VSN) due to a right-sided brain lesion (RBL) is characterized by the inability to perceive stimuli emerging in the area opposite to the side of brain damage [1,2]. VSN patients usually have lower scores on disability tests and require longer rehabilitation periods compared to stroke patients without neglect [3,4]. Thus, VSN influences most activities of daily living such as eating, reading, and getting dressed [2,5].

Besides adopting conventional rehabilitation methods to treat stroke-related VSN symptoms, the use of virtual reality (VR) in their assessment and treatment is becoming increasingly popular [6-8]. VR is defined as "an advanced form of human-computer interface that allows the user to 'interact' with and become 'immersed' in a computer-generated environment in a naturalistic fashion" [9]. Reasons for this increasing popularity might be found in the many advantages attributed to VR, for example, the ability to provide a safe but engaging environment [10], immediate feedback on performance, and repetitive task training with quantifiable continuous progression of training [9]. For example, VR training in isolation or in combination with conventional therapy approaches proved to be superior for the improvement of lower extremity function in stroke patients [11]. However, despite this, evidence for VR therapies being superior to conventional intervention methods for treating VSN is so far somewhat limited [6-8]. Evidence shows that VR has the capacity both to enhance current methods for the assessment and rehabilitation of VSN and to provide new ones. Tsirlin et al [8] presented three major challenges for successful implementation of VR systems in VSN therapy: (1) ergonomic aspects in the sense that mobile, lightweight VR systems are required for rehabilitation, (2) the complexity of VR systems insofar as treating clinic staff do not necessarily have programming skills, and (3) the prohibitive costs of VR devices (eg, for immersive VR systems with head-mounted displays or cyber gloves) [7,8,12]. For these reasons, VR rehabilitation platforms have been mainly restricted to laboratories and to prototypical systems [8] and have not been widely implemented in patients' homes.

A European research group, Rehabilitative Wayout In Responsive Home Environments (REWIRE), developed a game-based VR rehabilitation intervention trying to account for those challenges [13]: (1) the exergame station was designed as a computer workplace, allowing the patient to practice the exergames in a seated position, (2) the complexity of the user interface was reduced to a minimum by designing a game menu with large and clear icons to select a game, difficulty level, and playing time (Figure 1), and (3) the costs of the VR systems are relatively low, as the exergames are played on a personal computer, using the Novint Falcon haptic device (Novint Technologies) to control the games [14] (Figure 2). The Novint Falcon enables people to experience a realistic sense of touch by providing force and haptic feedback when reaching for and grasping virtual objects [14]. Furthermore, it can be operated with one hand only, thus permitting VSN patients to play the exergames with their unaffected upper limb.

When new VR interventions are designed, it is important to follow a phased iterative approach, wherein the usability aspects of such a management strategy, within the target population, are first assessed [15]. Usability is defined by the International Organization for Standardization (ISO) as "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [16]. "Specified users" do not only include patients but also therapists, as their requirements for the use of such games may differ from those of the patients [17]. Therapists may, for example, need an easy startup and configuration procedure, or stress that the games should be supportive not only for the patient during play but also for the therapist in tracking a patient's performance [17]. It is therefore important to assess both the therapists' and patients' opinions, as they will use the exergames at least as often as a patient.

Assessing opinions from users can be done by using questionnaires or by means of interviews. The former has the advantage to assess many opinions of a representative sample but cannot tell us about the meaning behind a response. The latter is usually applied in a smaller sample but provides personal thoughts from an insider's perspective [18]. To date, most studies used questionnaires to assess users' satisfaction with the intervention or product being tested [19-22]. Currently, there is a lack of evidence from studies examining the users' perspective via application of qualitative methodologies [23]. King et al [24] and Lewis et al [25], for example, used focus group and semistructured interviews to assess patients' satisfaction with their game intervention. All participants enjoyed playing the computer games. However, all stroke patients were in the chronic stage of recovery and none were diagnosed with VSN symptoms. Another qualitative report explored the perceptions and personal experiences of stroke survivors regarding a leisure-based VR program [26], reporting improved self-efficacy belief in leisure activities after the VR experience in in-depth interviews. However, the reported evidence was based on a single game session only.

Results of a recent systematic review state that in the posttest stage of usability evaluation, performing interviews to evaluate user perceptions of games is recommended, whereas the use of questionnaires is considered useful for evaluating user acceptance and satisfaction [27]. As a consequence, only a combination of both quantitative and qualitative data allows a full picture of user perspectives, as it is done in mixed methods research [18]. Therefore, the purpose of this study was to quantitatively and qualitatively assess the patients' and therapists' user perspective when using REWIRE exergames for rehabilitation of VSN symptoms due to a stroke. Specifically, we wanted to evaluate the (1) perceived-user friendliness of the exergames, (2) attitude towards using the exergames, and (3) intention to use the exergames in the future.

Figure 1. Game menu of the 9 neglect exergames.

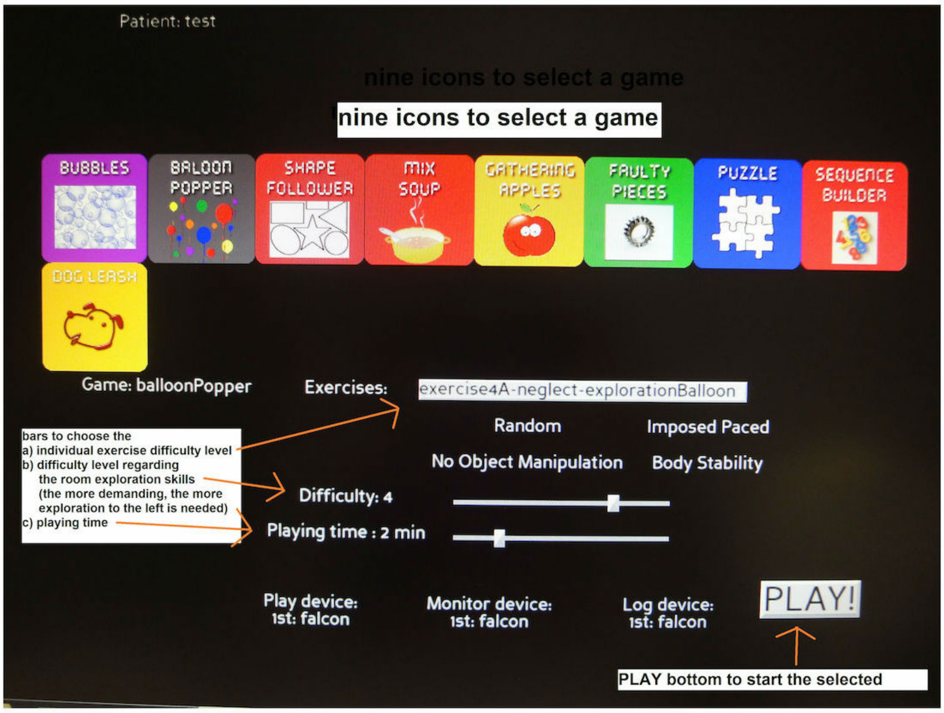
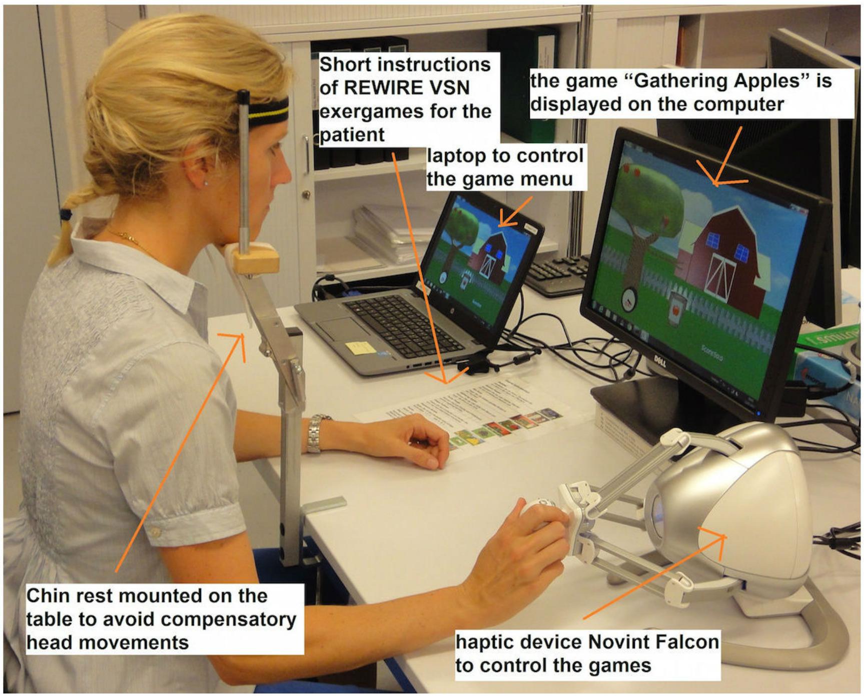


Figure 2. REWIRE exergames training station.



Methods

Study Design

For this usability study, we used a mixed methods design adopting the "sequential explanatory" design strategy [18]. This design strategy is characterized by an initial collection of quantitative data followed by a collection and analysis of qualitative statements. The purpose of this strategy is to use the qualitative results to assist in explaining and interpreting the findings of the quantitative data.

Participants

There were 2 groups of users involved in this study: patients as end users and therapists as experts.

The patient group included 7 adults with an ischemic (n=5 men) or hemorrhagic (n=2 women) RBL due to a first stroke with accompanying VSN symptoms as measured with the Catherine Bergego Scale (CBS) [28]. The CBS includes direct observation of the patient's functioning in 10 real-life situations. The functioning is rated from 0-30, where 0 indicates no neglect symptoms. These patients simultaneously participated in a feasibility study in which the exergames were evaluated, while taking part in this usability evaluation [29]. Their mean age was 68.6 (SD 8.9) years. Their stroke incidence took place 46.3 (SD 30.8) days before study entry. All patients were right-handed. Three participants were able to walk, while the others used a wheelchair for locomotion. Their CBS mean score was 9.4 (SD 5.1) points. All but one of these 7 patients identified themselves as having a computer at home prior to participating in the study.

The expert group consisted of therapists responsible for the treatment of the stroke patients during their inpatient stay. The 12 therapists (6 occupational therapists from one rehabilitation clinic and 6 neuropsychologists from another clinic) supervised and trained the patients in the use of the REWIRE exergames during the 3-week intervention phase. Their mean age was 33.3 (SD 5.7) years (range 27-45) with a mean work experience of 6.8 (SD 5.8) years (range 0.5-20). All therapists stated being familiar with the use of computers, rating their computer knowledge as excellent (n=3), good (n=8), and poor (n=1). All 19 participants signed informed written consent before study entry. We obtained ethical approval for the study from the local Ethics Committees (Zurich No. 2014-0543 and Bern No. 389/2014) as well as from Swissmedic (2015-MD-0003). The study is registered with ClinicalTrials.gov.

Setup of the Exergames Training Stations

We installed 2 exergames training stations, one in each of the collaborating clinics (Figure 2). The games were played at a table in a seated position either in a chair or wheelchair depending on the patient's motor skills. We used a 21-inch computer monitor at a distance of 60-65 cm to display the games and the haptic Falcon Novint device to control the games. The haptic feedback enabled the patients to experience a realistic sense of touch, for example, by feeling some resistance simulating the weight of the currently held virtual object in the virtual hand displayed on the screen (force feedback of the Falcon [14]) or a vibration when dropping, for example, a virtual apple in a virtual basket. The Falcon Novint was placed at the side of the computer monitor at a distance allowing the patients ease of reach with their nonaffected hand. A height-adjustable chin rest (Novavision GmbH) was mounted on the table to avoid compensatory head movements while playing the exergames.

REWIRE Visuospatial Neglect Exergames

We designed a series of 9 exergames aimed to improve exploration of the neglected side of space. During the development of the exergames, we regularly tested them in healthy controls prior to implementing them in a clinical setting. Their feedback was constantly integrated in the development process until consensus was reached. In order to maintain principles of training, game progression was individually adjustable through the selection of appropriate different levels of difficulty (more demanding meant more exploration towards the hemineglected side was required) [30]. The exergames content aimed to imitate activities of daily living (ADL), such as cooking a meal, following a recipe, gathering apples, walking a dog, and doing a puzzle. An overview of the 9 games and corresponding short instructions supporting their independent use are shown in Multimedia Appendix 1. A detailed description of the exergames can be found elsewhere [13].

Intervention

Both therapists and patients had the opportunity to test the exergames before entering the study, followed by a training event organized by the research team to learn, for example, how to handle the game menu and Falcon Novint haptic device. During the whole intervention phase, the research staff provided telephone or personal support whenever needed, for example, to handle technical problems with the training station. The exergames intervention lasted 3 weeks and included 15 training sessions each of approximately 30 minutes duration. Patients exercised with the games under supervision of the therapists depending on their required level of support, for example, to start a new game. The neuropsychologists included exergames playing in their computer group, meaning that participating patients played the REWIRE exergames while other group members performed alternative computer tasks. The occupational therapists (OTs) supervised their patients in a one-to-one setting during individual therapy sessions. Additionally, the supervising therapist individually adjusted the intensity of playing the exergames. This was done, for example, by changing the difficulty level or game duration in the game menu or by implementing short breaks between each game if needed. Each patient selected up to four REWIRE VSN exergames from the game menu to be played in a gaming session. The choice was based on personal interest of the patient, which was assumed to enhance motivation while playing. Therefore, during the 3-week intervention time, the patient was also allowed to change games if they wanted to test another game or felt bored with the previously played one. However, we suggested the patients test all of the 9 games at least once. Rehabilitation continued during the study intervention, our exergames serving as an additional therapy option to the standard program comprising daily occupational, physical, and neuropsychological therapy.

Outcome Measurements

Both patients and therapists completed a questionnaire at the end of the intervention. This included 12 questions with a 7-point Likert scale (1 point=strongly disagree; 7 points=strongly agree), evaluating (1) perceived user-friendliness of the exergames, (2) attitude towards using the exergames, and (3) intention to use the exergames in the future. The questionnaire design was based on an abridged version of the Technology Acceptance Model (TAM). TAM is an intention-based model developed specifically for explaining user acceptance of computer technology [31] that we considered useful for evaluating user acceptance and user satisfaction [27]. Patients received physical assistance from clinic staff to complete the questionnaire when incapable of writing or reading due to neglect. The therapists filled in their questionnaires independently. We analyzed the completed questionnaire responses and thereafter used them as a basis to prepare the individual interview [32] with the patients and the focus group interviews [33] with the therapists.

BC-T-A performed the audio-recorded individual interviews during the follow-up assessment planned for the feasibility study 4 weeks post-intervention. They focused on the patients' everyday life experiences with right hemispheric stroke and VSN symptoms during active rehabilitation and served as an opportunity to deepen, clarify, or confirm answers that were given in the TAM questionnaire. BC-T-A, who is an occupational therapist, took an active role during the interviews, aiming to build a relationship with the participants based on confidence and co-creation. Thanks to the many opportunities to meet the patients in the past (eg, while introducing the exergames to the patients or during data generation for the simultaneously running feasibility study [29]), a good basis to achieve this aim was already established.

We conducted the two focus group interviews in the collaborating rehabilitation clinics after the last patient had finished the REWIRE exergames intervention. We audio-recorded and filmed them. In comparison to individual interviews, focus groups represented group opinions influenced by social interactions and team dynamics, as therapists already knew each other well [34]. Therefore, they were an important complement to individually given answers via TAM questionnaires and served as a means for therapists to gain, share, or dispute experiences made with those exergames from their perspectives. During each interview, the moderator (BC-T-A) summarized the given answers on a flip chart, allowing therapists to add, complement, or change statements if needed. Additionally, the role of the moderator was (1) to balance the therapists' statements in terms of allowing/encouraging everybody to speak, while intervening when someone would have claimed too much time to speak and (2) to take care that all therapists' TAM answers were discussed that needed clarification while keeping the time set for the focus group interview.

We expected the acceptance of and satisfaction with the neglect exergame intervention to be good, which we defined as a total mean score of more than 4 points on the Likert scale, where 1-3 points meant no agreement, 4 points neutral, and 5-7 points agreement. The maximum achievable score was 84 points, indicating perfect agreement. For the individual and focus group interviews, we hypothesized that the users (therapists and patients) would have experienced the VR-based neglect training as supportive in treating VSN.

Data Analysis

To analyze the TAM questionnaires, we used descriptive statistics in SPSS software version 23. We calculated means, standard deviations, medians, and interquartile range values as appropriate.

We transcribed the individual interviews verbatim. Subsequently, we selected text passages from the entire conversation in which the interviewer (BC-T-A) and the patient discussed the use of the exergames and stored them separately. We used content and comparative analysis to analyze those passages [35,36], taking the following analysis steps: (1) reading the interview passages' transcriptions, (2) highlighting significant statements that provide an understanding of how the patient experienced the use of the exergames, (3) comparing those statements with the TAM questionnaire answers and assigning them to the three subcategories (user-friendliness, attitude, and intention to use in the future), and (4) writing a composite description of the patients' perspectives of using the exergames, while using quotes to underpin the interpretation.

We analyzed the two focus group interviews by drawing "Focus group Illustration Maps" (FIMs) [33]. The aim was to summarize the complex variety of statements and opinions without losing information or knowledge. Therefore, capturing the whole range of group knowledge is the essence of knowledge mapping, rather than highlighting the single statements of individuals. We took the following analysis steps: (1) listening to the audio recording while watching the video and taking notes, (2) comparing the notes and audio recordings together with the flipchart notes, (3) drawing the FIMs, re-watching the video to check the accuracy of the FIMs, (4) sending the FIMs to the participants for member checking, (5) incorporating feedback from participants into the FIMs if representative for the whole group, and (6) merging FIMs from both clinics into one FIM per subcategory from the TAM questionnaires, representing the opinions from all 12 participating therapists.

Results

We summarized the answers from the TAM questionnaires in Table 1 for patients and in Table 2 for therapists. Generally, the therapists took a more critical stance with a mean TAM questionnaire total score of 48.6 (SD 4.5) compared to the patients with a mean total score of 56.1 (SD 12.3). Their statements are presented according to the three subcategories of the TAM questionnaire. These are "perceived user-friendliness," "attitude towards using the exergames," and "intention to use the exergames in the future."

Table 1. Postintervention patients' TAM questionnaire responses.

Statement	P1[a]	P2	P3	P4	P5	P6	P7	Mean (SD)	Median[b] (Q_1/Q_3)	Mean (SD)
Perceived user-friendliness										
The exergames were easy to use.	5	6	7	7	7	6	5	6.1 (0.9)	6 (5/7)	5.6 (1.4)
The exergames manual was clear and understandable.	5	6	7	5	7	7	6	6.1 (0.9)	6 (5/7)	
Learning to use the exergames independently would be easy for me.	3	5	6	4	7	2	5	4.6 (1.7)	5 (3/6)	
Attitude towards using the exergames										
I generally have a positive attitude towards using the exergames.	5	7	2	6	7	1	6	4.9 (2.4)	6 (2/7)	4.8 (1.9)
I enjoyed exercising with the exergames.	4	6	2	6	7	5	3	4.7 (1.8)	5 (3/6)	
Exercising with the exergames…[c]										
was motivating.	4	6	2	7	7	4	5	5.0 (1.8)	5 (4/7)	
was exhausting.	3	7	1	3	4	7	2	3.9 (2.3)	3 (2/7)	
was a stupid idea.	5	7	4	6	7	5	4	5.4 (1.3)	5 (4/7)	
Intention to use the exergames in the future: If I had access to the exergames from at home, …										
I would use them in the future.	5	5	1	4	1	4	1	3.0 (1.9)	4 (1/5)	3.9 (2.1)
I would use them regularly.	4	5	1	4	1	3	1	2.7 (1.7)	3 (1/4)	
I'm convinced that my family/friends would support me using the exergames.	5	3	2	6	7	4	6	4.7 (1.8)	5 (3/6)	
I would recommend the exergames to other patients.	6	7	1	6	7	2	6	5.0 (2.5)	6 (2/7)	
Total score	54	70	36	64	69	50	50	56.1 (12.3)	54 (50/69)	
Mean (SD)	4.5 (0.9)	5.8 (1.2)	3 (2.4)	5.3 (1.3)	5.8 (2.4)	4.2 (2.0)	4.2 (2.0)			
Q_1	4	5	1	4	4.8	2.3	2.3			
Median	5	6	2	6	7	4	5			
Q_3	5	7	5.5	6	7	5.8	6			

[a]Patient

[b]Quartile 1=$Q_{0.25}$; Quartile 3=$Q_{0.75}$

[c]Positive statements: 1=strongly disagree / 7=strongly agree; Negative statements: 1=strongly agree / 7=strongly disagree

Table 2. Postintervention therapists' TAM questionnaire responses[a].

Statement	T1[b]	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	Mean (SD)	Q_1[c]	Median	Q_3[d]	Mean (SD)
Perceived user-friendliness																	
a)	6	5	6	7	7	5	5	5	5	6	6	4	5.6 (0.9)	5	5.5	6	4.9 (1.4)
b)	5	6	7	7	7	4	5	5	4	5	3	4	5.2 (1.3)	4	5	6.8	
c)	5	4	6	5	7	6	4	4	2	2	2	4	4.3 (1.7)	2.5	4	5.8	
d)	5	5	7	5	7	6	4	4	4	3	3	3	4.7 (1.4)	3.3	4.5	5.8	
Attitude towards using the exergames																	
e)	5	4	4	4	3	4	4	3	3	4	2	6	3.8 (1.0)	3	4	4	3.6 (1.4)
f)	4	3	2	4	2	4	3	4	4	3	4	3	3.3 (0.8)	3	3.5	4	
g)	7	5	7	3	3	5	4	6	3	2	6	5	4.7 (1.7)	3	5	6	
h)	1	3	1	1	2	3	1	4	1	3	2	3	2.1 (1.1)	1	2	3	
i)	4	5	3	3	2	4	3	4	4	4	5	5	3.8 (0.9)	3	4	4.8	
Intention to use the exergames in the future																	
j)	2	3	1	2	2	2	2	3	3	4	2	3	2.4 (0.8)	2	2	3	3.7 (1.8)
k)	7	6	7	7	6	7	6	5	6	5	5	5	6.0 (0.9)	5	6	7	
l)	2	4	2	2	2	4	2	3	3	4	2	3	2.8 (0.9)	2	2.5	3.8	
Total scores	53	53	53	50	50	54	43	50	42	45	42	48	48.6 (4.5)	42.3	50	51	
Mean (SD)	4.4 (1.9)	4.4 (1.1)	4.4 (2.5)	4.2 (2.1)	4.1 (2.4)	4.5 (1.4)	3.9 (1.4)	4.2 (0.9)	3.5 (1.3)	3.8 (1.2)	3.5 (1.6)	4.0 (1.0)					
Q_1	2.5	3.25	2	2.25	2	4	2.25	3.25	3	3	2	3					
Median	5	4.5	5	4	3	4	4	4	3.5	4	3	4					
Q_3	5.75	5	7	6.5	7	5.75	4.75	5	4	4.75	5	5					

[a]Positive statements: 1=strongly disagree / 7=strongly agree; Negative statements: 1=strongly agree / 7=strongly disagree. Statements:
Perceived user-friendliness
a) The exergames manual was clear and understandable.
b) I was easily able to train my patients for using the exergames.
c) Learning to use the exergames independently was easy for my patients.
d) I experienced learning to use the exergames as easy.
Attitude towards using the exergames
e) I generally have a positive attitude towards using the exergames.
f) The exergames were a gain for my patients.
g) The exergames were an unnecessary burden for my patients.
h) The exergames were a relief of responsibility for me.
i) The supervision of my patients was a pleasure for me.
Intention to use the exergames in the future
j) I can imagine using the exergames regularly as a training for my patients.
k) I generally believe that my workplace supports the use of VR training possibilities for my patients.
l) I would recommend using the exergames to other colleagues.

[b]T=Therapist

[c]Quartile 1=$Q_{0.25}$

[d]Quartile 3=$Q_{0.75}$

Perceived User-Friendliness

This subcategory was the most positively judged among patients with a mean 5.6 (SD 1.4) points and therapists with a mean 4.9 (SD 1.4). All patients agreed on the clarity of the manual and the ease of use of the exergames, while learning to use the exergames independently would not have been easy for patients 1 and 6 (P1 and P6; see Table 1). A possible explanation was the poor general computer knowledge that both patients identified. Thus there were associated uncertainties of what to do when sudden difficulties arose while playing, as stated by P6: "Sometimes I had difficulties in discharging the apples, and when I wasn't able to keep them steady over the basket, then the apples refused to drop into the basket" (P6). P2 had the same experience in another game with the "faulty pieces":

> *Yes, they [the exergames] sometimes weren't technically well set. You touched it [the fruit], but it didn't stick [to the virtual hand]* [P2]

To solve those difficulties in game control, P6 and P2 indicated that they contacted the supervising therapist for help. Using the Novint Falcon as haptic device to play the games was perceived as good by all patients. Patient P3 described that the device "acted up" now and then (not running smoothly or skidding of the whole device while playing), suggesting use of the mouse instead of the Novint Falcon as input device in order to solve this problem.

The therapists all agreed on the game manual's good understandability (Figure 3). They rated themselves as being capable of introducing the exergames to their patients (Table 2). However, they also stated that only the fitter patients were able to use the exergame station independently. For the more severely affected ones, guidance of the arm was necessary to play the games. This was experienced as no relief of responsibility for the therapists, which negatively influenced their attitude towards using the exergames (Figure 4). They further reported that some patients had difficulty understanding the purpose of the games. Therapists' reasons for this were given as being either (1) due to patients' poor self-awareness of their actual skills, making it difficult for them to explain to the patients the necessity of exercising their visuospatial exploration skills, or (2) due to the game design, which was experienced as being unappealing by both patients and therapists in combination with the abstract game control. The breakdown susceptibility of the software and the suboptimal posture, especially the use of the chin rest, were major critique points mentioned by most therapists (Figure 3). The former explained why therapists reported experiencing loss of valuable therapy time, as they often had to re-boot the system, keeping patients waiting while the computer restarted. Thus the exergames were rated as being somewhat impractical, although therapists recognized that they were testing in a pilot phase.

Figure 3. Focus group illustration map: perceived user-friendliness.

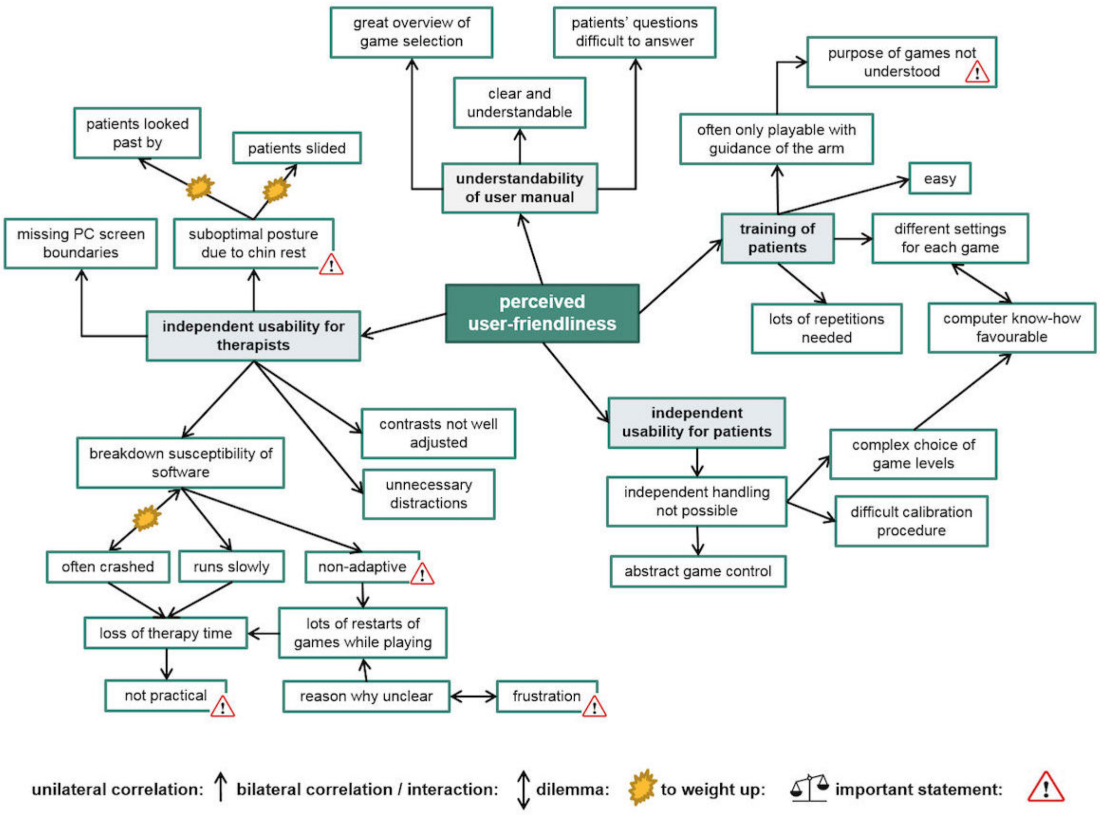
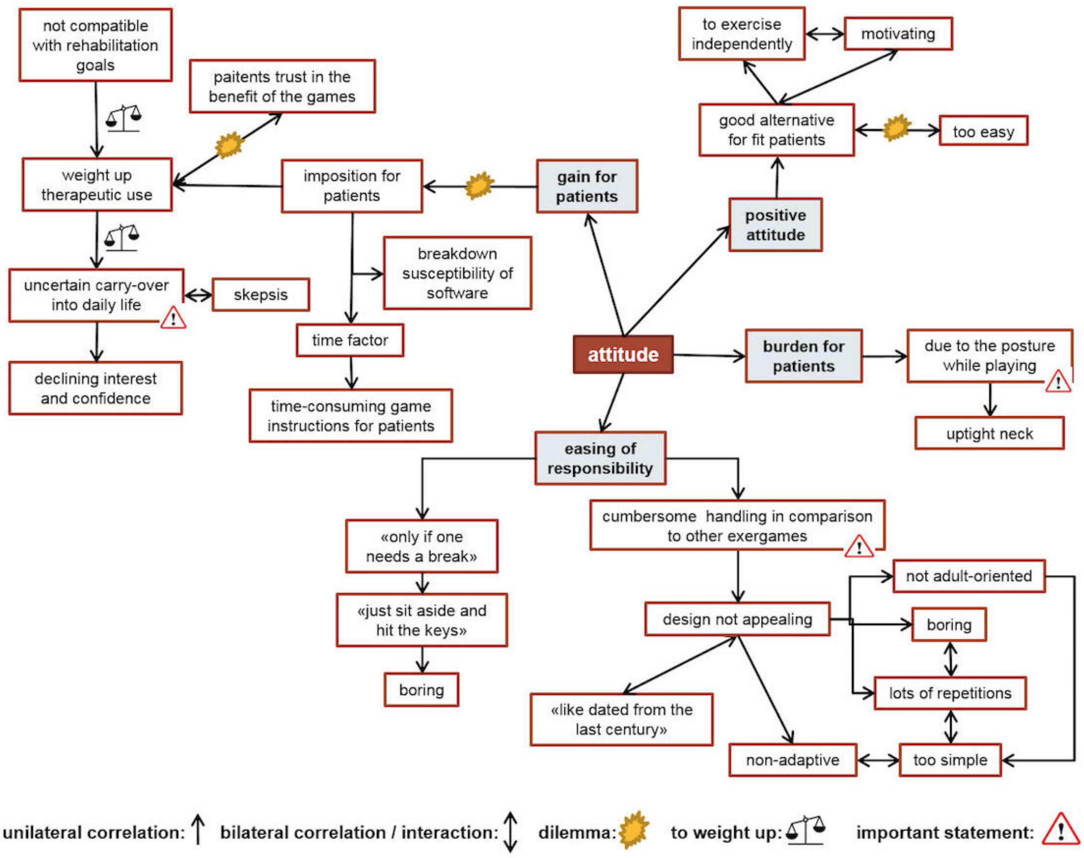


Figure 4. Focus group illustration map: attitude toward using the exergames.



Attitude Toward Using the Exergames

The general attitude of the patients toward the use of the exergames was 4.8 (SD 1.9) points (Table 1). The therapists rated it a mean total score of 3.6 (SD 1.4) points (Table 2). The patients experienced exercising with the games to be motivating and interesting and also as a "welcome change" to the conventional therapy methods provided in the Rehabilitation clinics: "Those games were a welcome diversion to normal neuropsychology, where you just sit face-to-face and have to do exhausting things all the time" (P5).

However, most patients preferred the conventional therapy methods over the exergames intervention, as they described it difficult to understand the purpose of the games:

> *In the beginning, I didn't really understand what all this meant; for what the games were good for. Then they [the therapists] explained it to me. After they had told me what aspects I had to pay attention to, then it was all good.* [P2]

> *I couldn't make sense out of it [the exergames]. I always had the feeling that the things there—those tests—were meant for ones with very severe brain damage, who weren't back on their feet yet. […] But not for me—I don't have such severe damage!* [P3]

> *I don't know what they [the exergames] would have been useful for. And no matter how much you have scored, you couldn't see the progress you had made.* [P6]

The patients experienced conventional methods as more effective than the VR intervention:

> *I didn't have the impression that it [the exergames intervention] did yield much. I experienced it as being a bit silly. I had the impression that the other things simply helped me much, much more. […] The eyes were not equally challenged to move back and forth.* [P6]

The content of the games was judged as "not bad" (P4). P4 perceived the exergame "puzzle" as being difficult because the puzzle template was displayed only once at the beginning, requiring the player to piece together the puzzle out of memory. The speed of the games and the related short reaction time was another difficulty mentioned by most patients as being experienced during play. They described being initially very motivated to play the games, but over the course of the 3-week intervention, their enthusiasm decreased, as they started to perceive playing the games as "boring" (P1, P4) and even "childish" (P1, P3):

> *You know, piling the ABC can be done by a first- or second-former! And to burst balloons that pop up out of a hole isn't very demanding either" (P3); and "Boring! In the beginning, it was good. But most recently…it was complicated to look through this thing [chin rest], you know. The other games they had were more interesting in a way.* [P4]

Using the chin rest while playing was the main reason why most patients experienced the exergames as exhausting (mean 3.9 [SD 2.3]):

> *This [chin rest] wasn't useful! I couldn't sit in an upright position and look through [the chin rest] to scan the whole computer screen. This was exhausting. You also weren't able to turn your head.* [P4]

The suboptimal posture of the patients while using the exergames was also problematic for the therapists (Figures 3 and 4). It was the main reason why some therapists rated them as an unnecessary burden. They described observing their patients sitting tilted to the left side in their wheelchair due to their VSN symptoms, watching past the chin rest instead of looking through it while playing. Furthermore, the therapists expressed reservations regarding the therapeutic use of the exergames. Those reservations were based on their uncertainty of achieving a carryover effect of visuospatial room exploration skills trained in a virtual environment into the real world. Additionally, they had difficulties in perceiving the VR intervention as supportive to achieve the patient's rehabilitation goal, namely to regain independence in daily life as well as possible. The therapists further described that their patients fully trusted them in the choice of therapy intervention to improve their skills (Figure 4). This blind trust gave the therapists a dilemma: on the one hand, they wished to use conventional therapy methods instead which they knew to be effective, but on the other hand, they recognized that the patients had agreed (and were eager) to participate in the study using this novel intervention. Despite this rather negative attitude towards exergames use, some therapists rated them as being a motivating alternative for fit patients to exercise independently, although they also rated them as being too easy for some patients.

Intention to Use the Exergames in the Future

Using the exergames regularly in the future was not viewed as conceivable yet, either among patients (mean 3.9 [SD 2.1] points) or therapists (mean 3.7 [SD 1.8] points). Most patients perceived the exergames as a good pastime and diversion that helped shorten the long days in the rehabilitation clinic (P4, P6, P7) but indicated that they would prefer doing activities other than gaming once back at home: "Up there [in the rehabilitation clinic], I thought that it is way better to do this [playing the exergames] than lying in bed or sitting on a chair while doing nothing" (P6). P5 and P7 described themselves as not being "a computer freak" (P7) or "a gamer" (P5) and therefore not wanting to use the games further at home. P3 missed the relevance to real life of the games, making the following suggestion for improvements:

> *Well, maybe tests that are more related to practice. You know, where you see: "Ah, this could be useful!" [...] For example doing an exercise you will need in the future when you want to drive a car again. Reaction or such things...which will help me to go ahead.* [P3]

For some patients, the games could have been more challenging and entertaining. P7 did not experience much pleasure while playing:

> *Not really...well, when I was successful, then I felt pleasure anyhow. Then I thought: 'Indeed, I am not as dull as I thought!' [...] It simply worked out somehow, but not as good that I would have felt pleasure to play more.* [P7]

Remarkably, most patients were nevertheless convinced that their family and friends would support them using the exergames at home. The patients also stated that they would recommend the exergames to other patients (Table 1). Reasons might be that the support of their relatives is taken for granted—no matter what they were doing to get better—and that they believe that trying everything to get better is the best rehabilitation strategy, including novel therapy methods like the exergames: "One should leave nothing undone, and try out everything!" (P7).

The therapists were not yet ready either to use the exergames in the future or to recommend their use to other colleagues—at least in the version used for this study—although all therapists were convinced that their workplace supports the use of VR training methods (Table 2). The neuropsychologists in particular were experienced in using the computer as a means of therapy and therefore accustomed to high-tech VR methods. The OTs, however, were rather restrained towards VR methods, some even fearful of being replaced by computers in the future (Figure 5). Barriers to future use of exergames were diverse and numerous; for example, the benefits of virtual versus equivalent real-life tasks was mentioned by the OTs, who expressed preference for the latter therapy option. The nonadaptiveness of the software was another barrier highlighted by the neuropsychologists, as they were used to exergames with this feature.

The therapists proposed suggestions for improvements for all mentioned barriers (see Figure 6), which, given that those improvements are implemented in a new version of the exergames, indicates that a new version of those exergames would be used in the future.

Figure 5. Focus group illustration map: intention to use the exergames in the future.

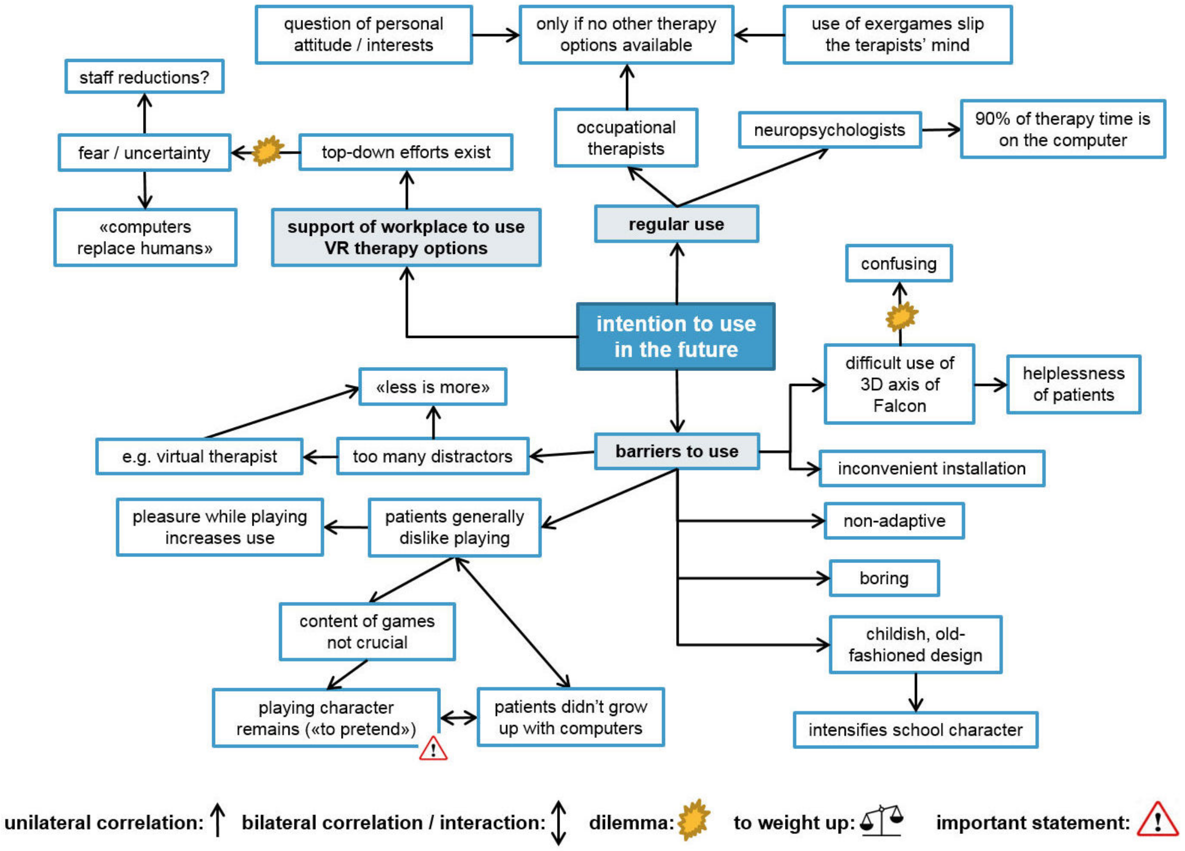
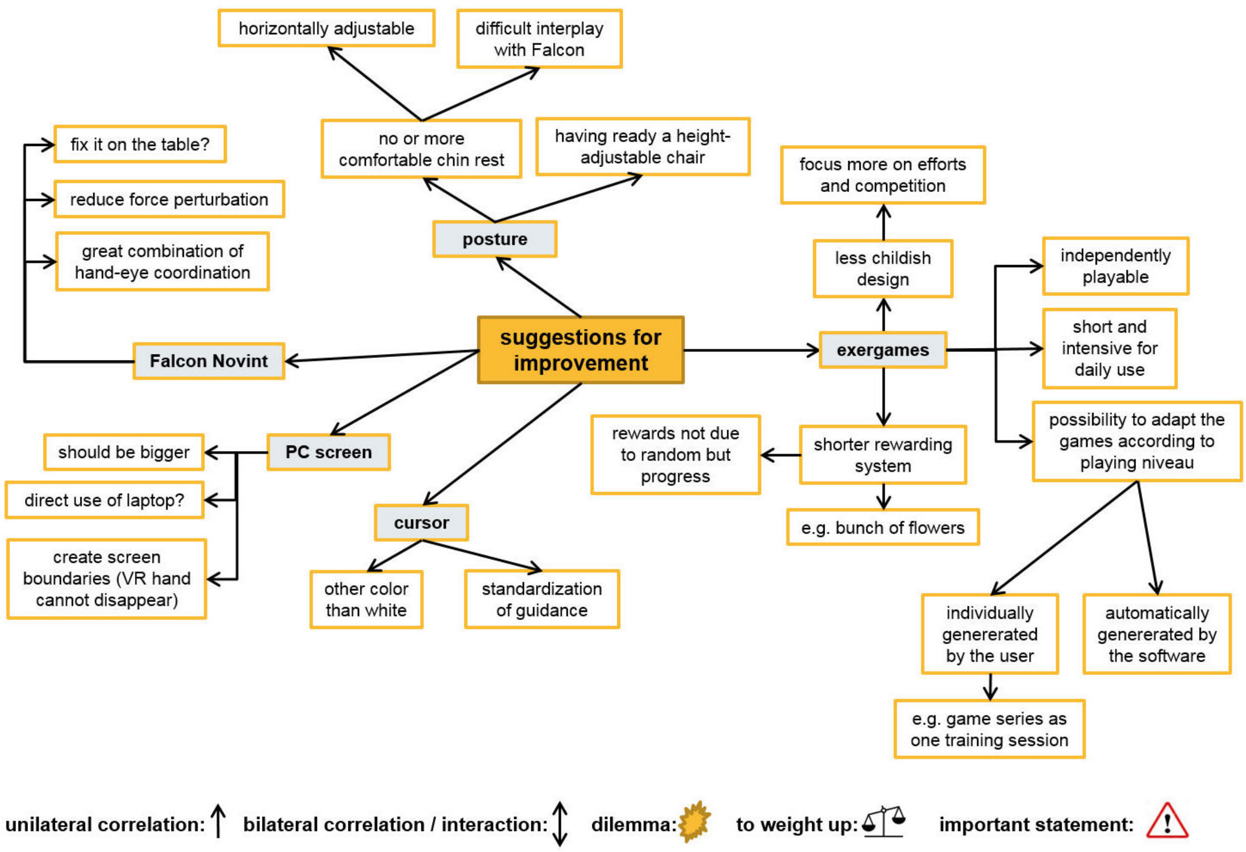


Figure 6. Focus group illustration map: suggestions for improvements of the game-based virtual reality intervention.



Discussion

Principal Findings

This usability study aimed to quantitatively and qualitatively assess user perspectives (patients and therapists) of using REWIRE exergames as a novel rehabilitation intervention to treat VSN symptoms due to stroke. The findings showed that the patients as end users generally rated the use of the exergames more highly than did the therapists. Most patients experienced the games as motivating, interesting, and a welcome diversion in their daily routine during their inpatient stay in the rehabilitation clinic. The feeling of joy and motivation while playing was also described in other studies assessing user perspective in stroke patients testing a novel VR intervention [23,37,38]. Those studies tested games aiming to improve motor control in the affected arm due to hemiparesis following stroke without VSN symptoms. In our study, the patients controlled the games with a haptic device using their unaffected arm, in order to focus on improvement of cognitive skills. Most participants liked using the Novint Falcon instead of the mouse to control the games. However, some patients described having difficulties in grasping and releasing virtual objects. They confirmed that in one game, they had to touch an object with the index finger of the virtual hand to grasp it and in another game with the palm of the hand. This discrepancy was experienced as being misleading. In order to standardize the game control, Mainetti et al [39] suggest optimizing the degree of overlap between the virtual hand collision region and the target collision region.

Our sample, however, suffered from neglect and a certain related level of anosognosia [40]. They nevertheless experienced pleasure while playing. This is in line with other findings from a satisfaction questionnaire where stroke participants with neglect symptoms indicated enjoyment of the VR experience [19]. Despite having fun while playing, the presence of anosognosia in our sample negatively influenced their understanding of the purpose of the exergames. Inability to fully understand the purpose of the intervention was also a topic in a focus group interview with stroke patients without VSN symptoms [24]. It is important to make sure that patients understand the game purpose, so as to meet their expectations and to avoid frustration [23]. Although we paid weekly visits to participating rehabilitation clinics to discuss progress and progression of the exergaming with patients and therapists, it nevertheless seemed difficult for some of the former group to understand the purpose of the treatment strategy. This was particularly the case for the more severely affected patients.

Mainetti et al [39] tested exergames in a single patient with chronic stroke who had VSN symptoms. This patient liked the exergames and was not bored while playing them. Most of our patients, however, experienced a decreasing enthusiasm during the 3-week intervention and started to perceive the activity as boring, even though games regularly and individually progressed and were designed according to therapeutic principles [13]. It seems that basing the selection of games on personal interest of the patient could not enhance motivation while playing either. Paying attention to the diversity and progression of game complexity is no guarantee of constant use and engagement over time. Other studies testing different VR interventions with patients with cerebral palsy also described a reduction in engagement over time [41,42]. Therefore, reasons for this decreasing enthusiasm other than a suboptimal balance of providing a challenge while still enabling success might be the time point of the intervention and the lack of feedback in the achieved game scores. Compared to other stroke samples [24,25,37,39], our patients were still in the early stage of recovery and were still hospitalized, therefore in the situation of receiving daily therapy sessions with which they could compare the REWIRE exergames. In this context, it is perhaps understandable that the exergames—still a test version—fell behind other VR therapy options that are long-established in the market. Furthermore, testing a novel therapy option with stroke patients in their chronic stage, when regular therapy often might have stopped, evokes hope for further motor or cognitive improvements and therefore increases motivation [25]. Another reason for the decreasing interest might be seen in the fact that our games did not display the achieved results after each training session, unlike Lewis et al's [25] submarine game, for example. Although this option was provided by the software, we had decided not to activate it, as the achieved scores after each game/session were not yet storable. This prevented the patients seeing progression over time. We were aware that being unable to see the achieved scores equaled a lack of feedback regarding the patient's personal progress. However, positive feedback and measures of success are critical components to enhance engagement [23,24]. There was a rewarding system after each REWIRE game (Figure 7), but as this was random and not performance-based, patients did not care for it.

The lack of feedback experienced by fitter patients, combined with their perceptions of being insufficiently challenged while playing the exergames, might be reasons why they indicated preference for conventional therapy methods with a "real" therapist over this VR intervention. Their experiences of the games as "a good pastime and diversion" suggests that most patients did not see this as a rehabilitation intervention per se, supporting their preference for conventional therapy. This is in line with other findings, where stroke survivors experienced the novel games as supplementary to conventional therapy, the latter being viewed as providing beneficial rehabilitation [25]. Conversely, the majority of patients in another study reported experiencing VR interventions as useful as conventional therapy [43]. The nature of play that is inherent to games may be perceived differently among adult patients, as the therapeutic benefit may not be as obvious as during conventional therapy, also depending greatly on how the virtual environments were designed [23]. It might be that having prepared a predefined set of games to be played during several training sessions while only progressing difficulty levels within the same games—as it was suggested by some of the therapists—might have helped patients perceiving the exergames as a (repetitive) rehabilitation intervention. However, we preferred letting them choose and switch games according to their individual preferences to (1) keep motivation as high as possible and (2) give them the opportunity to test all exergames during the intervention.

Figure 7. Rewarding system of REWIRE exergames.

The REWIRE game design was rated as having limited appeal by both therapists and patients. The therapists in particular wished to have games that would be self-adaptive to patient progress in order to experience ease of responsibility. For example, they missed the opportunity to prepare a series of games that would then automatically run through during an intervention session. The lack of facility within software for patients to save and return to previously achieved difficulty levels between sessions was also noted. Those features would allow the patient to start directly at the right difficulty level and subsequently play the game independently without the therapist needing to adjust the settings before and during the training session. Although the goal of such VR interventions is to create a game menu that patients can run themselves with little input from others, it is nonetheless imperative that an expert (ie, therapist) guides progression of the games to maintain the therapeutic basis of the intervention. In one study, where game speed and progression advanced automatically, the users were overwhelmed, which negatively influenced motivation and engagement in the game intervention [44].

Some of our patients indicated that they missed the exergames' relevance to real-life tasks—feedback also given by other stroke patients testing similar interventions [25]. This is despite the fact that we had tried to design them to be as much alike as possible. Male patients in particular perceived being able to drive a car as very important to them and therefore wished to be able to train those driving skills on the computer. Such conflicts with real-life expectations have also been described by Lewis and Rosie [23], suggesting a selection of environments that are deliberately unreal. Such simple environments have the advantage of avoiding unnecessary distractors by providing a restricted amount of stimulation, thus targeting the required rehabilitation effect. On the other hand, they comprise a risk of boredom and a related reduction in engagement for both patients and therapists.

When supporting patients to play the REWIRE exergames, some OTs expressed uncertainty in achieving carryover effects into real-life tasks. This uncertainty was one of the reasons why they would have preferred to use time for the training of real ADL rather than game play to achieve the rehabilitation goals set for their patients. Indeed, evidence for positive carryover effects of VR interventions into real life is limited [45,46]. For example, Gruskin et al [46] observed increased awareness of the involved extremity as well as greater carryover into ADL when using an auditory feedback device to alert a patient with left hemineglect when his flaccid upper extremity was in a dependent position. Gates et al [45] compared walking overground and on a treadmill surrounded by a virtual environment that applied optic flow in individuals with and without transtibial amputation. They found that both groups walked with similar overall kinematics (eg, knee flexion/extension) and kinematic variability (ankle, knee, or hip) on the treadmill as they did overground. Their results suggest that treadmill training in a virtual environment should be sufficiently similar to overground walking in the real world that changes carry over.

Further reasons why the therapists would have preferred use of rehabilitation time for conventional therapy rather than for testing the novel VR intervention was the breakdown susceptibility of the software—giving them the feeling of wasting too much therapy time. Additionally, the use of the chin rest forced the patients to sit in a nonergonomic posture. This posture was also the reason why many patients got tired while playing, rather than because of cognitive challenge. When planning this study, we did not expect the chin rest to be a major problem when playing the exergames. Its use was precipitated by a need to avoid compensatory movements of the head. However, according to the feedback of all participants, the use of the chin rest for a whole therapy session of approximately 30 minutes was too exhausting. We therefore recommend the use of a chin rest for short assessments only rather than for a whole therapy session [47]. Such technology limitations have also been described in other studies testing VR interventions [42,48]. For example, Wille et al [48] found a correlation between software failures and reduced ratings of fun while playing. Li et al [42] have described difficulties in positioning patients with postural impairments so that they were able to operate the VR system. Not surprisingly, such technology limitations are associated with negative feedback from the users, as was the case in our sample. Those limitations were also determinative of participants' ratings of limited intention to use exergames in the future. Other perceived barriers were not being a "gamer" (patients), as well as the fear of being replaced by computers in the future (OTs). The neuropsychologists did not share this fear, as they were more used to computer-based interventions than the OTs. As a consequence, the neuropsychologists as computer experts were the most critical users of our exergames.

Limitations

Some limitations of this study should be discussed. First, most of the stroke patients needed assistance in completion of the TAM questionnaire, either in retaining the paper-based questionnaire while it was on the table due to their hemiparesis, or in being helped to read the questions due to their VSN symptoms. Both of these issues may have influenced their responses. A touch-screen version on a tablet fixed on a table to avoid side slipping for those stroke patients who suffer from hemiparesis would allow questionnaire completion with one hand only. A button placed on the right margin of the tablet could be designed to audio-display the questions, making reading of the questions unnecessary. Second, the fact that the therapists participating in the focus group were working colleagues from the same team might also have influenced their interactions and utterances during the interview. For example, in both interview groups, the team leader was also present, which might have inhibited some participants in expressing what they really thought about the exergames. We therefore chose focus group illustration maps for data analysis. Together with the flip chart notes taken directly during the interview, those FIMs allowed a precise summary of the group statements without exposing someone through using quotes, where they might recognize the person who had said that. Third, the fact that the main researcher (BC-T-A) knew all participants quite well at the time point of the interview influenced her way of conducting the individual and focus group interviews. Holding preunderstanding about the patients' life from former meetings during data acquisition for the feasibility study might have influenced her way of formulating questions differently than when she would have met the patient for the first time. However, the interview quality probably had improved thanks to the already established relationship. Being an occupational therapist like half of the participating therapists further influenced the flow and conduct of the focus group interviews. However, speaking the same professional language might have facilitated formulating experiences made with the patients and exergames. Fourth, the recruitment of stroke patients with VSN symptoms in a clinical setting who were fit enough to test the game-based VR intervention was quite difficult. Testing such an intervention in a later, chronic stage where most patients are in a better health condition might have been easier. However, all patients were excited to take part in a research project during their inpatient stay and they cherished being asked for their personal opinion not only in a questionnaire, but also in a face-to-face interview.

Future Work

Lewis and Rosie [23] were entirely correct in their statement that “it may appear impossible to design a system that appeals to all users” (p. 1884). However, we should not overlook the fact that, despite all the critiques mentioned by users, most patients enjoyed playing the exergames. The criticisms identified are a motivator to improve the existing game design in order to achieve an optimal rehabilitation effect. Therefore, before thinking about testing the REWIRE exergames in a larger controlled trial of stroke patients with VSN, for example, the game design should first be modified according to the suggested improvements. Decisions should be made regarding the degree of realism of the virtual environments: should we design environments as unreal as possible [23], or as real as possible by using a tool such as Google Street View [19], for example? Immediate feedback of the achieved game scores should be implemented together with a graphical overview of the changes over time to enhance engagement and motivation. The flexibility of the software should be increased, for example, by creating a function to save the chosen difficulty level for each game. Future work could examine if the frequency and time of game play—in our study on a daily basis over 3 weeks—or if providing a predefined set of exergames to be played instead of having free choice of game selection, influences user perspectives on the exergames. Results have shown that the use of a chin rest to control compensatory movements of the head is not recommended for a whole therapy session. Furthermore, evidence is needed to explore possible carryover effects of such VR interventions into real life in order to enhance acceptance of such interventions among therapists.

Conclusion

This study provided insight into user perspectives based on quantitative and qualitative statements of stroke patients suffering from VSN and therapists using novel exergames to explore the hemineglected left space in an inpatient setting. The results showed that all users perceived the REWIRE exergames as user-friendly, but that they would not necessarily entertain their use in their current format. The general attitude toward using the exergames was more positive among the patients than among the therapists. Recommendations for improvements of the exergames were mainly formulated by the therapists. Feedback suggests that once those recommendations could be realized, then the REWIRE exergames intervention could be explored using further trials. It is therefore of the utmost importance that end users (patients) and experts (therapists) are involved in order to achieve acceptable and user-friendly VR game-based rehabilitation methods.

Acknowledgments

This work was partially supported by the Rehabilitative Wayout in Responsive Home Environment (REWIRE) project (www.rewire-project.eu), funded by the European Commission under the FP7 framework with contract 287713, and by the Occupational Therapy Association of Switzerland [no grant number available].

We warmly thank the 19 participants who were willing to share their time and opinions with us to realize this study. Further thanks go to the two collaborating clinics where the study took place, namely the Zürcher Reha Zentrum Wald, Canton of Zurich, Switzerland, and the Klinik Bethesda, Tschugg, Canton of Berne, Switzerland. Further thanks go to Laura Wiederkehr, former masters student of the ETH Zurich, for her invaluable help in this research project, and to Martin J. Watson, PhD, for proofreading the manuscript for English and structure.

Authors' Contributions

BC-T-A designed the study; provided support in designing the exergames; conducted the acquisition, analysis, and interpretation of the data; and wrote the manuscript. E-S provided support in designing the study, developed the exergames, and contributed to editing the manuscript. ED-dB, NA-B, and RH-K initiated the study and contributed to editing the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest

None declared.

Multimedia Appendix 1

REWIRE VSN exergames: Short instructions for the patient.

[PDF File (Adobe PDF File), 205KB - games_v5i3e18_app1.pdf]

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Abbreviations

ADL: activities of daily living
CBS: Catherine Bergego Scale
FIM: Focus group Illustration Map
OT: occupational therapist
RBL: right-sided brain lesion
REWIRE: Rehabilitative Wayout in Responsive Home Environments
TAM: Technology Acceptance Model
VR: virtual reality
VSN: visuospatial neglect

Edited by G Eysenbach; submitted 10.05.17; peer-reviewed by S Yang, N Skjaeret; comments to author 31.05.17; revised version received 12.07.17; accepted 27.07.17; published 25.08.17.

Please cite as:
Tobler-Ammann BC, Surer E, Knols RH, Borghese NA, de Bruin ED
User Perspectives on Exergames Designed to Explore the Hemineglected Space for Stroke Patients With Visuospatial Neglect: Usability Study
JMIR Serious Games 2017;5(3):e18
URL: http://games.jmir.org/2017/3/e18/
doi:10.2196/games.8013
PMID:28842390

Publisher:
JMIR Publications
130 Queens Quay East.
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