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Virtual Rehabilitation Environment Using Principles of Intrinsic Motivation and Game Design

Abstract

This paper presents a novel multimodal virtual rehabilitation environment. Its design and implementation are based on principles related to intrinsic motivation and game design. The system consists of visual, acoustic, and haptic modalities. Elements contributing to intrinsic motivation are carefully joined in the three modalities to increase patients' motivation during the long process of rehabilitation. The message in a bottle (MIB) virtual scenario is designed to allow interplay between motor and cognitive challenges in the exercising patient. The user first needs to perform a motor action to receive a cognitive challenge that is finally solved by a second motor action. Visual feedback provides the most relevant information related to the task. Acoustic feedback consists of environmental sounds, music, and spoken instructions or encouraging statements for the patient. The haptic modality generates tactile information related to the environment and provides various modes of assistance for the patient's arm movements. The MIB scenario was evaluated with 16 stroke patients, who rated it positively using the Intrinsic Motivation Inventory questionnaire. Additionally, the MIB scenario seems to elicit higher motivation than a simpler pick-and-place training task.

1 Introduction

Rehabilitation after a stroke is a long process and may not be successful if a patient is not committed. Therefore, it is important to determine which factors stimulate and encourage the individual to participate in the rehabilitation process with great enthusiasm. One important factor is motivation, which is frequently used as a determinant of rehabilitation outcome (Maclean, Pound, Wulfe, & Rudd, 2002). Researchers distinguish between intrinsic and extrinsic motivation. Intrinsically motivated behaviors are "those that are freely engaged out of interest without the necessity for separable consequences; to be maintained, they require satisfaction of the needs for autonomy and competence" (Deci & Ryan, 2000). On the other hand, extrinsic motivation pulls us to act due to factors that are external to the activity itself: threats (Deci, 1975) or rewards such as peer admiration (Wood, Griffiths, Chappell, & Davies, 2004).

Most patients have extrinsic motivation to be rehabilitated, so it is important to also support their intrinsic motivation, which can be greatly influenced by design features of the rehabilitation task that the patient is performing

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(Colombo et al., 2007). We can thus gain knowledge and ideas for supporting the patient's motivation and promoting engagement and enjoyment from other fields such as game design and motivation in learning.

Intrinsic motivation theory (Malone, 1980) asserts that the most important elements that make game-playing fun and engaging, as well as sustain players' continual motives, are challenge, fantasy, control, curiosity, cooperation, recognition, and competition. Intrinsic motivation can also be supported by elements such as improving your highest score, getting your name on the hall of fame, mastering the machine (Wood et al., 2004), role playing, narrative arcs, challenges, interactive choices within the game, and interaction with other players (Dickey, 2006). Two important factors that help motivate learners to continue playing are goals and interaction features. Goals should be of different levels (Swartout & Van Lent, 2003): short-term goals (lasting a few seconds), medium-term goals (lasting a few minutes), and long-term goals (lasting the length of the game). Games should provide a balance between complete freedom of interaction and too much control, a concept called the regime of competence (Gee, 2003). According to this principle, the player should be challenged to the edge of his or her ability.

An online study assessed structural characteristics that are important to a group of self-selected video game players (Wood et al., 2004). One of the main overall findings was the importance of a high degree of realism (realistic setting, sound, and graphics). Among other important characteristics were customization, rapid absorption rate, winning and losing, and a variety of control options. Researchers also examined four different game types (Amory, Naicker, Vincent, & Adams, 1999). The most stimulating and highest-rated were adventure and strategy games, suggesting that players preferred games with objectives requiring higher-order thinking skills and creative problem solving (i.e., cognitive challenge). Ribbens and Malliet (2010) identified seven factors of perceived game realism: simulation, freedom of choice, character involvement, perceptual pervasiveness, authenticity regarding subject matter, authenticity regarding characters, and social realism.

Motivation (intrinsic, extrinsic) and engagement are the result of complex interactions between the player and the game. However, the interaction capabilities are different for healthy subjects and stroke patients. The two groups differ in both comprehension and motor capabilities. While some of the elements related to intrinsic motivation might not be affected by the neurological condition, the way the subject interacts with the environment must be reconsidered when tasks are optimized for a patient population. In multimodal scenarios, the interaction is composed of visual, acoustic, and haptic modalities, which need to be properly addressed.

Visual feedback provides most of the information related to the task. However, the complexity of visual feedback needs to be relatively low in order to not confuse the patient. Pathologies such as neglect also have to be taken into account. While visual feedback provides most of the instructions related to the training task, haptic feedback generates tactile information about interactions with the virtual environment. Additionally, the robotic device used for haptic rendering can provide support for patient movements (e.g., Krebs et al., 2007; Nef, Mihelj, Colombo, & Riener, 2007). Thus, the role of a haptic interface is twofold and becomes threefold if its capability of objective measurements is considered (Harwin, Patton, & Edgerton, 2006). Force and position sensors built into the device provide high-quality information about the patient's motor performance, allowing assessment of rehabilitation progress.

Acoustic feedback also has an important role in motor rehabilitation. The influence of sound and in particular music on humans during the history of humanity has been enormous. It is also known that music treatment can be used to prevent significant increases in subjective anxiety, heart rate, and systolic blood pressure (Knight & Rickard, 2001). Not only music, but speech and sounds are also very important for multimodal perception and rehabilitation. In our previous research on virtual rehabilitation (e.g., Ziherl, Novak, Olenšek, Mihelj, & Munih, 2010), we found that robotic assistance by itself can confuse patients. If they cannot predict when and which way the robot will move, they are likely to either try to perform all the work themselves or let the robot do everything. In standard rehabilitation practice, the therapist guides the patient verbally as well as physically. For example, if the patient needs to perform a lifting motion, the therapist will say “now, let’s raise the arm” as he or she begins guiding the patient. Thus, combining robotic assistance with verbal guidance would make the task easier to understand and lead to improved performance. Furthermore, the robot could also provide encouraging statements to complement a successfully completed task or reassure the patient when performance is poor. Robots with spoken encouraging comments have already been implemented in rehabilitation (e.g. A. Tapus, L. Tapus, & Matarić, 2008), but have not been combined with haptic assistance.

Due to the complexity of human-robot interaction during rehabilitation, each of the contributing modalities needs to be carefully considered. A novel rehabilitation scenario that exploits the main influential elements was constructed with the goal of increasing the patient’s intrinsic motivation during robot-delivered therapy. These are then presented through visual, acoustic, and haptic modalities. A variety of choices were implemented to extend the training beyond simplistic pick-and-place or trajectory guidance tasks. The main novelty of the scenario is the interplay between the motor and cognitive challenges. The first challenge is a prerequisite for motor learning, while the second was identified as an important motivator in game playing. This introduces a completely new concept in motor (and possibly cognitive) rehabilitation, which was not exploited before. The scenario was finally validated within a group of stroke patients.

2 Scenario Design

2.1 General Specifications

The Yerkes–Dodson law defines the relation between motivation/arousal and learning. An intermediate level of arousal is required for optimal performance (Yerkes & Dodson, 1908). In order to challenge/arouse and motivate the patient at an optimum level, the training scenario must adhere to certain requirements. These requirements are often contrary to the most important postulate of motor rehabilitation that requires frequent repetition of motor tasks. Frequent repetitions inevitably lead to boredom after a certain period of exposure. Since motor tasks need to be relatively simplistic, they do not provide a cognitive challenge that would engage and arouse the patient. Therefore, a task can be envisioned in a way that would challenge the patient at both the cognitive and motor levels. Interplay between the different types of challenges would make the training scenario more entertaining and engaging. It would also allow patient-specific cognitive rehabilitation, which is often separated from motor training. However, a scenario targeting cognitive and motor training would have to be adaptable to specific patient capabilities defined by cognitive and motor deficits. This would make the adaptation of task difficulty more complex, but could lead to better improvements in motor and cognitive capabilities.

A task that addresses these issues and complies with requirements for augmenting intrinsic motivation is presented in the following sections. Its most obvious characteristic is that it alternates between a primarily cognitive challenge and a primarily physical challenge. However, the two challenges are interlinked such that completion of a cognitive challenge requires a motor action and vice versa.

2.2 Message in a Bottle Training Scenario

The Message in a Bottle (MIB) scenario takes place on an exotic island (see Figure 1) with different areas (see Figure 2) through which the user proceeds as he or she advances through the levels of the scenario. The user standing on a beach sees the island and its surroundings from a first-person perspective. The main component of the scenario is a bottle (see Figure 1[a]) with an enclosed message floating toward the user. The bottle has to be caught by manipulating (motor action) the rehabilitation robot end-effector equipped with a grasping mechanism. Catching the bottle represents a short-term goal of a primarily physical nature (though some cognitive activity is involved in motion planning). Once the bottle is caught, the message from the bottle appears on the screen and two boats float into the view of the user. The message forms a question with two possible responses (see Figure 1[b]), one correct and one false. The question provides a cognitive challenge. The user answers the question by

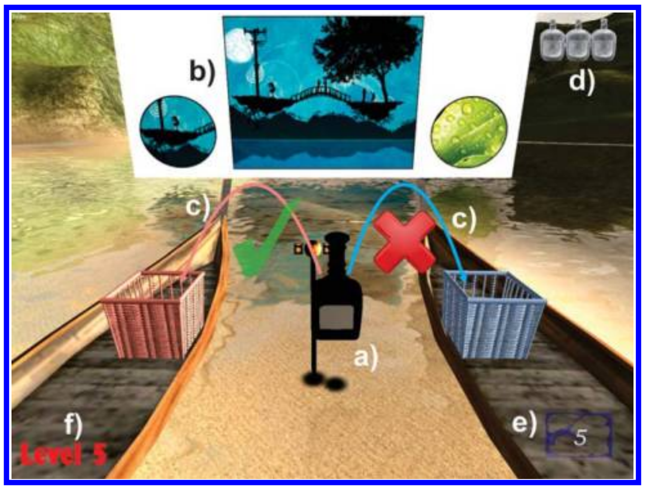

Figure 1. *(a) Short-term physical goal (catch the bottle), (b) cognitive challenge (which answer is correct, left or right; left is correct in this case, tick and cross are not visible in the patient's scenario), (c) physical goal, place the bottle into the correct basket (left or right), (d) immediate feedback (number of collected bottles), (e) points (competition), (f) medium-term goal (episodes).*

placing (motor action) the bottle into the basket (see Figure 1[c]) on the boat that is closer to the correct response. Placing the bottle again provides a short-term physical goal. The task is a classic pick-and-place task with the addition of a cognitive challenge that breaks the monotony of simple arm movements.

Overall, the scenario provides the user with a sense of role playing, curiosity (hidden message in the bottle), and fantasy (life on an exotic island). It provides a short-term goal—first catch the bottle floating in the water and later place it in the correct box; a medium-term goal—areas and episodes on the exotic island (see Figure 1[f]); and a long-term goal—reaching the final level, finding a treasure, and finishing the game. The user gets immediate feedback through the number of collected bottles (see Figure 1[d]). To better keep track of his or her progress, the user receives points (see Figure 1[e]) for each successfully completed action. Points are received for every caught bottle, every placed bottle, and

Figure 2. *Three exotic island area snapshots that correspond to different difficulty levels.*

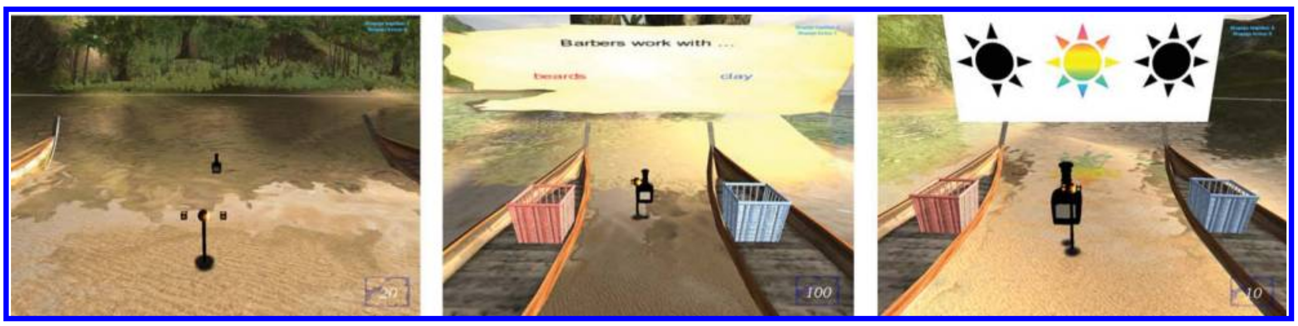

Figure 3. *Different scenario phases with textual and graphical questions: this scene is shown when the subject is catching a bottle, when the question is presented in a textual form and when a question is presented in a graphical form; the center and right images also present different difficulty levels determined by the height of the baskets where the bottles are placed.*

every correctly answered question. This induces a sense of competition in some subjects. For instance, a user may try to obtain a higher score than another user or simply a higher score than he or she had obtained in a previous session.

Once the user successfully catches and places a certain number of bottles, he or she advances to the next area of the island with a different visual and audio background (Figure 2). As the user progresses to the next area, the average difficulty of the motor task increases. Progress through the different areas depends exclusively on the user's success in catching and placing bottles and does not depend on the user's success in answering the questions. This progress through the areas induces a sense of accomplishment of medium-term goals as well as keeping the scenario from becoming too boring. The user may even be curious how the next area will look, or may prefer one area over another. The graphics and sounds of the scenario are quite realistic.

The questions hidden in the bottles cover a variety of interesting topics. There are over 300 questions in total, divided into nine categories: science, mathematics, history, geography, sports, art, nature, general, and music. They are presented from all categories evenly, and the same question is never given twice to the same subject. Since the questions all have two possible answers, they are set up so that, at lower difficulties, the questions are not a strong distractor (i.e., the answer is very obvious) while at higher difficulties, both answers are possible and require the subject to think carefully. The difficulty of the questions was rated independently by two psychologists on a scale from 1 to 10, and a third rater was consulted when the opinions of the first two raters differed by more than two. Questions and answers can be presented in textual as well as various graphical (e.g., puzzle) forms. Answering questions requires higher-order thinking skills, making the game challenging from a cognitive perspective. In combination with motor activity, the scenario provides an interesting interplay between cognition and motor actions.

What makes the MIB scenario attractive is the possibility of using questions to allow the subject to influence the unfolding of the scenario. In addition to general questions with true and false answers, questions about the subject's mood (e.g., Do you feel good?), physical state (e.g., Are you tired?), and game parameters (e.g., Is task too easy?) are randomly presented to engage the user without cognitively overloading him or her. Such questions provide immediate information about the user preferences and overall state and can be used to adapt the task to make it more suitable for each patient.

In order to make the training engaging and motivating, the MIB scenario is composed of visual, haptic, and acoustic modalities that provide real-time feedback to the patient.

2.3 Visual Modality

The visual modality provides the subject with the most complex information about his or her surroundings. Most of the elements presented through the visual modality are shown in Figure 1, Figure 2, and Figure 3. The number of objects, default sizes of the objects, color combinations, and color palette are selected to be pleasant, encouraging, and calming for the user. The photorealism is kept at an appropriate game level that does not require too much computational power but nonetheless provides an attractive appearance.

2.4 Haptic Modality

The MIB scenario is haptically rendered through a rehabilitation robot. The virtual environment consists of haptic objects, detection of collisions between environment objects, and force generation algorithms for rendering various aspects of interaction with the environment.

The haptically rendered objects in the scenario are the bottle, two baskets, and the water. The robot end-effector is modeled as a haptic interaction point in the virtual environment. The size, weight, and speed of the bottle as well as the height and positions of baskets can be modified during the task. The feeling of interaction with the water is simulated by viscosity when the subject lowers the robot end-effector below the virtual water level. Additionally, the robot provides various modes of physical assistance for patients' movements, as shown in the following sections.

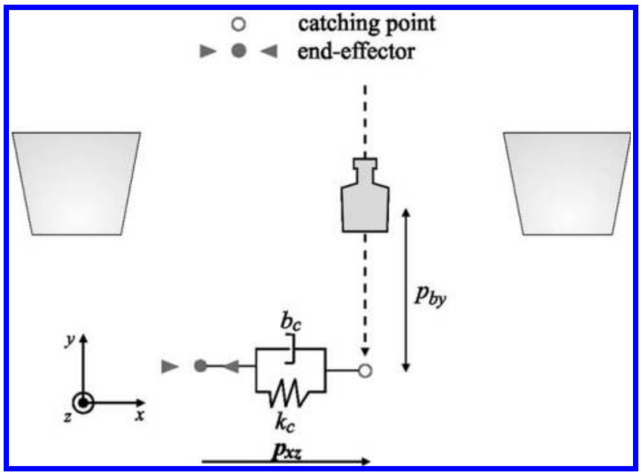

Figure 4. *Catching assistance leads the subject in xz plane to the catching point with an impedance controller.*

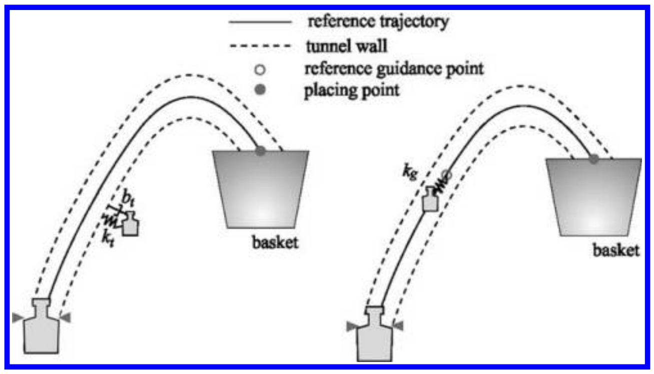

Figure 5. *Two impedance controllers included in the tunnel assistance. The controller that allows only small deviations from the central trajectory is shown on the left side. On the right side, the guidance controller leading the subject's arm along the desired trajectory is shown.*

2.4.1 Catching Assistance. For subjects unable to independently reach toward the bottle, the catching assistance gently pulls the patient's hand toward the point where the floating bottle is to be intercepted. It is implemented as an impedance spring-damper system with stiffness k_c and viscous damping b_c that guides the subject's arm in a frontal xz plane (see Figure 4). The assistance starts to generate forces when the bottle reaches the center of the workspace. The force then increases when the bottle is approaching the lower end of the screen (the catching point). Vector $\boldsymbol{F}$ is the computed force while vector $\boldsymbol{p}_{xz}$ is the deviance of the end-effector from the catching point. Vector $\boldsymbol{v}_{xz}$ indicates the velocity of the robot end-effector in the xz plane. The normalized parameter p_{by} is equal to 1 when the bottle is at the center of the workspace and equal to 0 when the bottle reaches the catching point.

$$\boldsymbol{F} = \left(1 - p_{by}\right)\left(k_c \boldsymbol{p}_{xz} - b_c \boldsymbol{v}_{xz}\right).$$

2.4.2 Grasping Assistance. For subjects who are unable to perform manual grasping, the grasping assistance causes the bottle to stick to the virtual gripper. Additionally, the bottle is automatically released when the subject reaches the basket. If grasping assistance is disabled, the grasping force produced by the subject needs to be higher than a predefined minimal grasping force required to hold the bottle. The minimal grasping force can be changed during the task according to the subject's grasping abilities.

2.4.3 Tunnel Assistance. The haptic tunnel constrains movement trajectories to an arc extending from the point where the bottle is caught to the point where the bottle is dropped (see Figure 5). An impedance controller generates a force field that allows only small deviations perpendicular to the central trajectory. The control points for the reference trajectory are approximated using B-splines from trajectories obtained from neurologically intact subjects' point-to-point reaching movements (Ziherl, Podobnik, Sikic, & Munih, 2009). The guidance assistance leads the subject's arm along the desired trajectory with a force tangential to the direction of the haptic tunnel. A separate impedance controller is used to compute the assisting force.

2.4.4 Adaptive Haptic Assistance (Alternative to Tunnel Assistance). It has been shown that when moving the hand between two points, a healthy person tends to follow a straight line, minimizing movement jerk (Flash & Hogan, 1985). Such optimal trajectories are often used for implementation of tunnel assistance. The patient, on the other hand, often cannot exert such an optimal movement due to muscle coordination impairment. Instead, patients might generate sufficient voluntary movement toward the target by following the path that meets their muscle coordination capabilities.

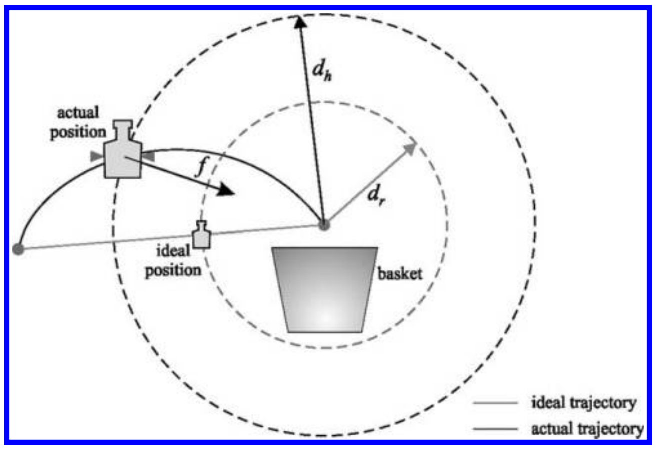

Figure 6. *Adaptive haptic support.*

For this reason, to allow the patients to arbitrarily select the most comfortable trajectory, haptic support should only impose the movement of a patient's hand toward the target position within finite predefined completion time without predefining the actual movement trajectory.

The adaptive assistance controller is focused on point-to-point reaching movements. Given the starting and the target positions, the reference time course is determined by minimizing the movement jerk. The result is a time-based trajectory, which only determines the reference distance with respect to the target position at a certain time, but does not prescribe the actual reference hand position (see Figure 6). The adaptive haptic support is then determined according to the error between the reference d_h and the actual distance d_r of the patient's hand and realized with a first-order impedance-based feedback controller (stiffness and viscosity), with controller stiffness applied only when the patient's hand is lagging behind the reference hand position ($d_h > d_r$). If the patient decreases the error between the actual d_h and the reference d_r hand distance from the target, the game scenario gradually decreases controller stiffness until the optimal movement dynamics that meet the patient's capabilities are reached. On the other hand, if the patient performs better than expected by the reference distance ($d_r > d_h$), controller stiffness is set to zero. The task is also adapted to the patient's capabilities by adaptively adjusting the required task completion time (a time constraint for the patient to complete the bottle placing movement). Specifically, if the patient performs well, the required completion time might be too long, which often results in decreased patient motivation and voluntary engagement. For this reason, the required completion time is computed as the average of completion times of the few last successfully completed reaching attempts. A detailed overview of the adaptive haptic controller is given in Mihelj, Nef, and Riener (2007).

2.5 Audio Modality

The presence of the audio modality extends the realistic impression of the virtual environment. A variety of choices (e.g., different types of music, sounds on/off, environmental sounds, instructional and praising statements, etc.) gives the user a sense of control and engages him or her.

Environmental sounds reflect the presence of naturally occurring events and noises that one would expect on a tropical island (birds, water, trees, and wind). These sounds either occur randomly or are linked to haptically and visually rendered events.

Just like visual appearance, music importantly influences the subjective emotional experience. However, while the visual appearance of the scenario changes in response to the user's progress, thus giving a sense of progression, music is extremely subjective and cannot be changed identically for the same user. Genres that some users enjoy may be unpleasant to others, and thus induce a negative mood or even present a source of cognitive interference that would prevent the challenges from being successfully completed. The MIB scenario takes this into account. The user is allowed to preselect different types of music (rock, pop, folk music, classical, instrumental) depending on his or her preference and mood. This enables a more pleasant game experience. For each of the different music types, professionals were asked to classify a list of music compositions based on relevant musical features (Gomez & Danuser, 2007) such as accentuation, tempo, and rhythmic articulation, and how they are related to the perceived environment atmosphere. While the user is able to state his or her preferences regarding the music type, the MIB scenario adaptation algorithm selects the most appropriate music parameters based on the subject performance and task difficulty level (e.g., higher difficulty level means faster music tempo; if the subject is stressed, music becomes more relaxing and subtle).

The role of the therapist in classical rehabilitation is much more than mere manipulation of the patient's limb. A therapist has a complete overview of the patient's state in terms of biomechanics, physiology, and psychology. Thus, he or she can do much more than just silently manipulate the patient's arm. An important task for the therapist is verbal guidance: providing the patient with real-time instructions related to the task. We observed several stroke rehabilitation sessions administered by an occupational therapist. The statements addressed to the patient by the therapist were written down and can broadly be divided into instructions (Let's move left) and encouragement (Good job!).

Such instructions and encouragements can also be artificially reproduced in a context-sensitive manner (the statements relevant to our scenario were recorded by a female voice actor). Robot capabilities in terms of overall patient state analysis cannot match that of a therapist, but enough information might still be available for the robot to enable computer generated verbal instructions. The adaptive haptic support algorithm (see Section 2.4 for details) computes the required assistive force and its vector in space. Based on force vector parameters, instructions for the patient can be generated as presented in Figure 7. The force vector with a length exceeding a predefined threshold triggers an instruction, which is then selected based on the vector direction. Voice commands will guide the subject by instructing him or her how to move the hand and when to release the object to successfully complete the task. For instance, if the patient needs to move his or her arm to the left to reach an object, the statement "Let's move left" is played. If haptic assistance is enabled, the robot simultaneously begins to gently move the patient's arm to the left. In addition to instructional statements, the computer also generates calming and praising statements (when the bottle is missed or placed in the basket). The combination of all statements continuously stimulates the user to strive for better performance while exercising, compliment a successfully completed task, or reassure the player when performance is poor.

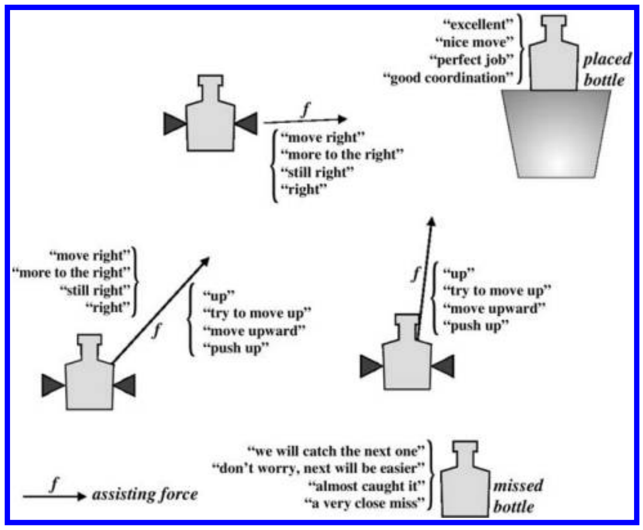

Figure 7. *Verbal instructions, picked by an adaptive algorithm, are used for user encouragement in various stages of the movement task.*

2.6 Interplay Between Motor and Cognitive Challenges

As stated previously, in the MIB scenario, the user needs to perform a motor action (catch the bottle) in order to receive a cognitive challenge (a question that needs to be answered). This cognitive challenge is then completed via another motor action (place the bottle in the appropriate basket). This creates a unique combination of physical and cognitive activity suitable for upper or lower extremity training that sustains the user's engagement. Variations of parameters of all three subtasks enable both simple as well as highly demanding scenario setups. Although the patient has to repeat the same pick-and-place motor task for a prolonged period of time, the task seems different each time the difficulty changes. To provide a regime of competence, the difficulties of the reaching motions and questions change independently. Therefore, even though the patient has to repeat an easy motor action many times, he or she is still challenged from the increasing difficulty of the questions. For patients with cognitive deficits, it is possible to keep the question difficulty low and independently increase the complexity of the motor tasks, thus allowing users to focus their cognitive abilities on the task of arm movement planning. Task difficulty adaptation is one of the most critical design parameters for engaging and motivating the patient.

2.7 Task Difficulty Adaptation

Motor and cognitive tasks difficulties are controlled independently. While complexity of the cognitive task depends only on the ratio of correct and incorrect answers, motor task complexity adaptation depends on more variables. The average task difficulty is defined by the different locations on the island representing increased difficulty (see Figure 2). In addition, task performance and biomechanical measurements are used to estimate whether a lower or higher difficulty would be optimal for the subject, and then parameters of the scenario are changed accordingly. Such a task difficulty adaptation system has been shown to be beneficial for upper extremity rehabilitation (Cameirão, Bermúdez i Badia, Oller, & Verschure, 2010). Eight different difficulty levels were implemented for use with this option. The lowest difficulty level contains very slow bottles (requiring approximately 15 s to cross the screen) and very low baskets (so that the subject does not need to lift his or her arm much) while the highest difficulty level contains very fast bottles (approximately 2 s to cross the screen) and very high baskets (requiring the subject to lift his or her arm very high).

The rules needed to adapt task difficulty were obtained using supervised learning, that is, from previously recorded training data. These data were obtained from 10 healthy subjects (all male, age 28.7 ± 5.6 years) using an experimental protocol previously used in our work (Novak, Mihelj, Ziherl, Olenšek, & Munih, 2011). Each subject began performing the scenario at level 3, 4, 5, or 6 (randomly chosen). After 1 min of performing the task at that difficulty level, the task was paused briefly and the subject was asked whether he or she would prefer the difficulty of the task to increase or decrease. Subjects were not given the option to stay at the same difficulty level. Once the subject had stated his or her preference, the difficulty changed by one or two levels in the direction chosen by the subject. This randomness was introduced in order to expose subjects to a wider range of difficulty levels and create a more robust training data set. After task difficulty was changed, the task began again at the new difficulty level. In total, the subject went through six 1-min periods, with the subject's preference noted and the difficulty changing after each one. After the final task period, the experiment was concluded.

Eleven features were calculated from the raw signals for each 1-min task period. They can be divided into two groups: task performance (three features) and biomechanics (eight features). Performance features describe how well a subject did during a particular time period. The three features used were the difficulty level (1–8), the percentage of caught bottles, and the percentage of bottles placed into the basket. Biomechanical features describe the forces and movements applied by the subjects. The eight features used were mean absolute force, mean absolute velocity, mean absolute acceleration, total work, mean frequency of the position signal, mean frequency of the velocity signal, mean frequency of the acceleration signal, and mean frequency of the force signal.

These features must then be fused into a common estimate of how task difficulty should be changed. During the training data collection, subjects were regularly asked whether they would prefer the next task difficulty to be easier or harder, and their responses were noted. Assuming that the responses were true and accurate, this gave us a training data set with known inputs (performance and biomechanics) and known desired outputs (subject's preference). Since there are only two possible outputs (increase/decrease difficulty), it is possible to use any of several available classification methods (e.g., discriminant analysis, neural networks, support vector machines, etc.) in order to translate input to output. We chose to use stepwise linear discriminant analysis since it is a relatively simple, widespread method that also includes feature selection. It has been used for task difficulty estimation and adaptation in various applications, including air traffic control (Wilson & Russell, 2003) and rehabilitation robotics (Novak et al., 2011). It is used to find a linear combination of features which best separate data points into two or more classes. In our case, it was used to estimate whether difficulty should be increased or decreased. Its accuracy was judged according to how its

Figure 8. *Experimental setup.*

estimate matched the subject's preference regarding task difficulty in leave-one-out cross-validation of the training data.

Stepwise linear discriminant analysis matched the subject's preference in 90.3% of cases in training data cross-validation. It was thus judged to be sufficiently accurate and added to the scenario. However, it should be noted that the abilities, preferences, and needs of patients are not necessarily the same as those of healthy subjects, and that ideally the training data should consist of patient measurements instead.

3 Clinical Evaluation

3.1 Hardware

The HapticMaster robot, developed by Moog FCS, was used as the haptic interface. Its endpoint was equipped with a two-axis gimbal and a passive grasping module. The subject's arm was supported by two cuffs fastened above and below the elbow. A 1.4 × 1.4 m screen was used to display visual data. Subjects sat approximately 1.25 m in front of the screen. A photo of the experimental setup is shown in Figure 8.

3.2 Patient Motivation Assessment

The first clinical evaluation of the scenario was aimed at assessment of the level of motivation among patients. Sixteen subacute stroke patients from the University Rehabilitation Institute of the Republic of Slovenia were recruited for a brief evaluation. There were 10 males and six females (age 46.2 ± 13.4 years, age range 22–61 years). They were diagnosed with intracerebral hemorrhage (five subjects) or cerebral infarction (11 subjects). As a result of the stroke, 11 suffered from hemiparesis of the left side of the body and five suffered from hemiparesis of the right side of the body. The time between stroke onset and the experiment session was 128 ± 64 days. All were cognitively intact and only moderately physically impaired.

Table 1. *Intrinsic Motivation Inventory Results During the First Clinical Evaluation*

	Maximum possible	Mean ± *SD*
Interest/enjoyment	35	27.3 ± 6.3
Perceived competence	28	21.7 ± 4.3
Effort/importance	28	23.6 ± 3.5
Pressure/tension	35	14.1 ± 6.5
Value/usefulness	35	28.3 ± 5.0

Upon arrival, the subjects were informed of the purpose and procedure of the experiment, then signed an informed consent form. Then, they were seated in front of the HapticMaster, and the affected arm was strapped into the device. The MIB scenario was demonstrated, and subjects exercised with it for 6 min. The Intrinsic Motivation Inventory (IMI) questionnaire was presented in order to evaluate subjects' opinions of the scenario, and an informal interview was conducted regarding the experience.

The IMI is a questionnaire that has been used to assess patient motivation in a variety of settings, including motor rehabilitation (Colombo et al., 2007). We used a 25-question variant of the IMI with five subscales: interest/enjoyment, perceived competence, effort/importance, pressure/tension, and value/usefulness.

As seen in Table 1, the results of the IMI showed a favorable response to the MIB scenario on all subscales. This shows that the MIB scenario is highly motivating for patients and does not evoke pressure or tension. During informal interviews, patients with a higher level of physical impairment emphasized the usefulness of the adaptive haptic support, and liked the naturalness of the grasping.

3.3 Task-Related Motivation Assessment

Having found that the MIB scenario is highly motivating for patients, we wished to see whether this motivation is caused by the elements of the MIB scenario or is simply a consequence of any robot-assisted rehabilitation. Specifically, we wanted to see if a simpler scenario would also elicit a comparable level of motivation. Six subacute stroke subjects participated in this evaluation (all male, age 59.3 ± 10.6 years, age range 48–77 years). All were diagnosed with cerebral infarction. As a result of the stroke, five suffered from hemiparesis of the left side of the body and one suffered from hemiparesis of the right side of the body. The time between stroke onset and the first experiment session was 233 ± 103 days. All were cognitively intact and only moderately physically impaired.

In addition to classical therapy, each subject also participated in four robot-assisted rehabilitation sessions: two with the MIB scenario and two with an apple scenario. The second is a simple scenario consisting only of picking up apples from the ground and placing them into a basket (Podobnik, Mihelj, & Munih, 2009). Sessions were held twice a week (once with one scenario, once with the other) for two weeks. The session was led by the therapist who adjusted the parameters of the scenarios (level of haptic assistance, type of music, task difficulty level) according to the user's preference and his or her own professional opinion. The IMI was filled out after each session. After the last session, the subjects received an additional questionnaire asking them to express their preferences regarding the scenarios including specific features of the MIB scenario. Since the goal was to keep the robot-assisted rehabilitation sessions as natural as possible, each session consisted of the subject exercising with the scenario for as long as he wanted (five-minute minimum).

No significant differences between the two scenarios were found in responses to the IMI. However, the IMI, though it had been previously validated for use in rehabilitation (Colombo et al., 2007), was found to be rather complicated for patients, especially when judging statements including a negative. For instance, several patients had trouble understanding that answering "Strongly disagree" to the statement "I was not able to perform the task well" means the same thing as "I was able to perform the task well." Four out of six subjects strongly preferred the MIB scenario, one had no preference, and one (who had trouble comprehending the questions posed in the MIB scenario) preferred the apple scenario (see Figure 9). The results from some of the other questions posed in the final questionnaire are illustrated in Figure 10. These results, although limited by a small sample size, suggest that complex, game-like scenarios can increase patient motivation by providing an interesting challenge. However, an MIB-type scenario may not be suitable for cognitively impaired subjects.

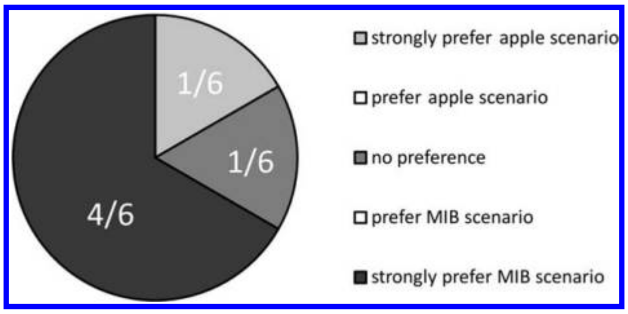

Figure 9. *Patients' scenario preferences. See text for explanation.*

4 Discussion

Clinical evaluations showed that subjects enjoyed exercising with the MIB scenario. Though the IMI did not show significant differences between the MIB scenario and the less complex apple scenario, the subjects emphasized their liking of the new MIB scenario in both the final questionnaire and the informal interviews. Thus, it appears that such rich scenarios can motivate the patient and make therapy more interesting for him or her. Nonetheless, certain issues should be considered.

Most importantly, we must ask whether such a complex scenario actually leads to a better rehabilitation outcome. Though our study covered only a few therapy

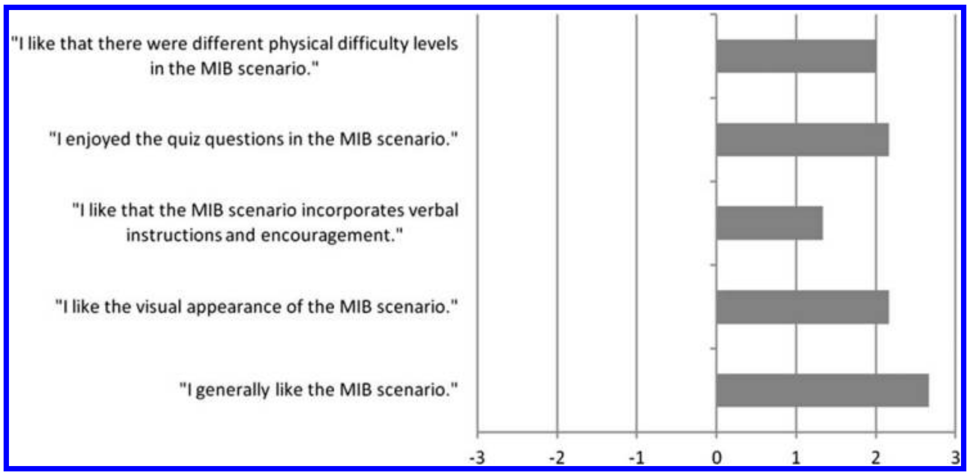

Figure 10. *Subjects' responses to the final motivation questionnaire. Mean values for responses of six subacute patients are shown.*

sessions per patient, we already discovered that cognitively demanding scenarios can actually confuse the patient. This was evident with the patient who preferred the apple scenario to the MIB scenario, since he had trouble comprehending the quiz questions. Furthermore, the medical doctors and therapists at the University Rehabilitation Institute stated that they felt that the MIB scenario would not be suitable for severely cognitively impaired patients due to the verbal complexity. Based on this information, we developed a second version of the scenario where the questions are graphical (see Figure 1 and Figure 3, right) rather than verbal (see Figure 3, middle). In limited testing, this version has proven to be more popular among certain patients. Nonetheless, the issue remains that it has not yet been proven whether the increased attractiveness of the scenario actually leads to more physical exercise; rather, the focus on the questions could distract the patient and lead to less exercise being done in the same amount of time. Clearly, an optimal trade-off between scenario attractiveness and physical exercise intensity must be found.

Nonetheless, game-like elements of the scenario were noted to increase motivation, even in some unexpected ways. For instance, after exercising with the scenario, participating patients talked with each other about their experience and compared their performance. Other elements are necessarily subject-specific. For example, some patients like different types of music during exercise while others prefer none at all. Similarly, some patients require haptic assistance while others do not. Tuning these elements, however, is quite simple and can lead to improved mood (in the case of music) or improved task performance (in the case of haptic assistance). However, each element can also evoke a negative response from users if used inappropriately (e.g., loud music for stressed patients, haptic assistance for patients who do not need it). Thus, a step toward optimizing the scenario would be to evaluate the effect each element has on patients and thus decide whether it should be included (in order to make the scenario more interesting) or excluded (in order to avoid distracting the patient). Such evaluations would necessarily be different for different groups of patients; for heavily impaired patients, the MIB scenario likely would not be beneficial since they need to focus on the movement itself and do not need additional cognitive challenges.

Furthermore, though each element can be considered separately, it is also important to note that the different elements also interact with each other in order to evoke a certain mood in the subject. Two elements that induce a positive experience by themselves may lead to distractions or annoyance when presented together. For this reason, though our scenario attempts to alternatingly provide physical challenges (moving the bottle) and cognitive challenges (answering the questions) while evoking a pleasant mood in the user (using audiovisual stimuli), these three components cannot be completely separated (i.e., moving the bottle also requires some cognitive activity, and failure to successfully move the bottle may worsen the user's mood), and complete therapy consists of physical, cognitive, and affective factors interacting with each other. Balancing these different factors can be very difficult.

The affective component can be especially problematic to evaluate; while the level of physical activity can be evaluated by the user's success in moving the bottle and the level of cognitive activity can be evaluated by the user's success in answering the questions, the patient's affective state is difficult to measure but at the same time influences overall performance. For instance, measuring user motivation can be done with the IMI as in our study, but the questionnaire can only be administered once the therapy is over and may result in inaccurate results for patients who have trouble answering it. Here, an emerging trend of game design could perhaps be considered: the field of affective gaming, where various objective and automated measures such as gestures, facial expressions, and physiological measurements are used to infer the user's affective state and react to it within the context of the game in order to preserve the user's emotional balance (Gilleade & Dix, 2005; Hudlicka, 2009). Such games have already been implemented in rehabilitation using psychophysiological measurements (Novak et al., 2011; Koenig et al., 2011), but are not yet suitable for clinical practice due to the complexity of properly evaluating the user's affective state.

5 Conclusions

A novel type of a training scenario for motor rehabilitation is presented. The novelty is introduced through a combination of alternating motor and cognitive challenges presented to the exercising patient. The interplay of the two challenges breaks the monotony of infinite repetitions of similar limb movements required for improvement of motor functions. This results in increased engagement and motivation of the patient, hopefully leading to a better rehabilitation outcome.

The developed MIB scenario is multimodal and stimulates the user's visual, aural, and tactile senses. The rehabilitation robot also provides various modes of physical support, including a novel adaptive algorithm, while the acoustic modality introduces a concept of virtual therapist that provides instructions for the patient. A combination of adaptive physical support and spoken instructions for the patient's arm movements generates a close approximation of a human therapist. The difficulty of the task is updated based on the performance and biomechanical data of the patient.

The proposed scenario is based on a task that requires reaching and grasping, resulting in a kind of a pick-and-place application. The task is not a perfect match of an activity of daily living, but one can imagine similar scenarios related to activities of daily living that would incorporate all the basic elements of the MIB scenario. A possible scenario would be set in a kitchen where different ingredients would have to be used in a virtual implementation of a cooking task. In this case, cognitive task questions could be related to food preparation recipes.

The combination of motor and cognitive challenges in the MIB scenario is completely new and, to our knowledge, has not been previously used in any robot-based rehabilitation scenario. Scenario validation in a group of stroke patients shows positive responses to such training. Patients preferred this scenario over a simple pick-and-place task often used for rehabilitation purposes. The proposed scenario can be further upgraded to allow not only motor but also cognitive rehabilitation of stroke patients. However, the different elements of the scenario should be carefully analyzed, as each element can either encourage and motivate or confuse and upset the patient. Furthermore, the interplay between physical, cognitive, and affective experiences should be considered, as all three interact with each other during rehabilitation.

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