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River multimodal scenario for rehabilitation robotics

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Abstract—**This paper presents the novel "River" multimodal rehabilitation robotics scenario that includes video, audio and haptic modalities. Elements contributing to intrinsic motivation are carefully joined in the three modalities to increase motivation of the user. The user first needs to perform a motor action, then receives a cognitive challenge that is solved with adequate motor activity. Audio includes environmental sounds, music and spoken instructions or encouraging statements. Sounds and music were classified according to the arousal-valence space. The haptic modality can provide catching, grasping, tunnel or adaptive assistance, all depending on the user's needs. The scenario was evaluated in 16 stroke users, who responded to it favourably according to the Intrinsic Motivation Inventory questionnaire. Additionally, the river multimodal environment seems to elicit higher motivation than a simpler apple pick-and-place multimodal task.**

Keywords-psychophysiology; rehabilitation robotics; intrinsic motivation; multimodal interaction, haptics

I. Introduction

Rehabilitation after stroke is a long process. Therefore, it is important to figure out which factors stimulate and encourage the individual to maintain the rehabilitation process with great enthusiasm. One important factor is motivation, which is frequently used as a determinant of rehabilitation outcome [1]. 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" [2]. On the other hand, extrinsic motivation pulls us to act due to factors that are external to the activity itself: threats [3] or rewards such as peer admiration [4].

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 [5]. 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 [6] asserts that the most significant 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 be also supported by elements such as improving your highest score, getting your name on the hall of fame, mastering the machine [4], role-playing, narrative arcs, challenges, interactive choices within the game and interaction with other players [7]. Two important factors that help motivate learners to continue playing are goals and interaction features. Goals should be of different levels [8]: 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 [9] called "Regime of Competence". According to this principle, the player should be challenged at the edge of his or her abilities.

An online study [4] assessed structural characteristics that are important to a group of self-selected video game players. 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 character development and customization, multiplayer features, rapid absorption rate, multiplayer features, winning and losing features (e.g. ability to save the game, accumulating points and finding bonuses) and a variety of control options.

Researchers [10] also examined four different game types. Students identified graphics, sound and storyline as important aspects of games. The most stimulating and highest-rated among them were adventure and strategy games, which suggests that players preferred games with objectives requiring higher-order thinking skills, creative problem solving and decision-making.

The influence of sound and in particular music on humans during the history of mankind has been enormous. Music and sounds can be important in discriminating the subjective emotional experience. Diverse effects are practically impossible to quantify within some general forms. [11] report that the musical features with the most important contribution to distinguishing between negative and positive excerpts are mode, rhythmic articulation, and harmonic complexity. The biggest contribution to distinguishing between low-arousal and high-arousal are accentuation, tempo, and rhythmic articulation. It is also known that music treatment can be used to prevent significant increases in subjective anxiety, heart rate, and systolic blood pressure [12].

Not only music, but speech and sounds are also very important for multimodal perception and rehabilitation. Therapists provide patients with constant instructions on how to best perform an exercise, with simple comments, with praise when a task is successfully completed or with encouragement when the patient is having trouble.

In addition to the visual and sound modalities, the haptic interaction enables enriched cognition of the virtual environment (the training scenario in rehabilitation robotics). A number of publications, including our own, describe the haptic background, which will thus not be covered here.

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The first step of our work was to systematically analyze each of the contributing modalities. Based on that, a rehabilitation scenario for the stroke population was constructed that exploits the main influential elements. A variety of choices were implemented to extend the training way beyond simplistic pick-and-place or trajectory guidance in haptics.

II. Scenario design

A. Hardware

The HapticMaster robot [10], developed by Moog FCS, was used as the haptic interface. Its end-point 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 1.4x1.4-meter screen was used to display visual data. Subjects sat approximately 1.25 meters in front of the screen.

B. Cognitive challenge

In the River scenario, Figure 1, the user needs to perform a motor action (picking up 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 (placing the bottle into the appropriate basket). This creates a unique combination of physical and cognitive activity, suitable for upper or lower extremity stroke or other training, all in order to maintain the user's engagement. Diverse attributes in all three modalities enable both simple as well as highly demanding scenario setups. Although the patient has to repeat the same motor task (picking and placing) over and over again, the task seems different each time as the difficulty changes. To provide a »regime of competence«, the difficulties of motor and cognitive tasks change independently. Therefore, even though the patient has to repeat an easy motor task many times, he or she gets challenged by the increasing quiz difficulty and vice versa.

C. Virtual rehabilitation task

In the River scenario, the user finds himself on an island where bottles with messages are floating towards him. Overall, the scenario provides the user with a sense of role-play and fantasy and gives a long-term goal – finding a treasure and finishing the game.

In every area, the user's short-term goal is to use the robot to first catch and later place bottles floating on the river toward him. Each bottle carries a message that can be either a quiz question, a question about the user's mood, a question about the game or a question for extra points.

The quiz questions can cover a variety of topics. Each question has two possible answers, one true and one false. The user answers the question by placing the bottle into the left/right boat basket, depending on where the correct answer is located. The quiz incorporates higher-order thinking skills and challenge in the game. Additional questions about mood, game and for extra points are mixed with quiz questions to engage the user without cognitively overloading him or her. Questions and answers can be provided in textual form as well as various graphical (e.g. puzzle) format.

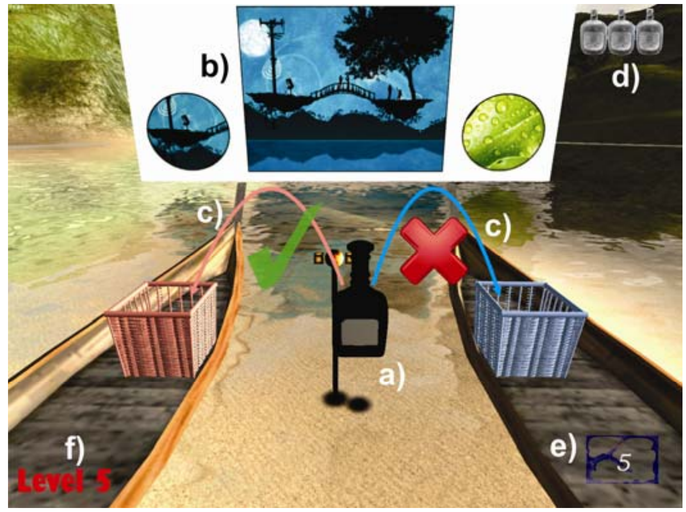

Figure 1. a) Short-term physical goal (catch the bottle), b) cognitive challenge (which answer is correct – left or right), c) physical goal – place the bottle into the correct basket (left or right), d) immediate feedback (number of collected bottles), e) points (competition), f) medium-term goal (episodes).

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. As the user progresses to the next area, the difficulty of 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 quiz questions. This progress through the areas induces a sense of accomplishment of medium-term goals as well as keeps the scenario from becoming too boring. The user may be even curious how the next area will look, or may prefer one area over another. The graphics and sounds of the scenario are rendered in a realistic way.

To better keep track of his or her progress, the user receives points for each successfully completed action. Points are received for every caught bottle, every placed bottle and every question correctly answered. This induces a sense of accomplishment as well as a competitive element. 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.

D. Visual modality

Visual interpretation of the river gaming scenario provides the main interaction between the game and the individual. The number of objects, default size of the objects, color combinations and color palette are selected to be pleasant, encouraging and calming for the user. Three of the island's environments are shown in Figure 2. The graphical appearance in the phases of scenario are depicted in Figure 3, before catching the bottle, with a text question and with a simpler graphical question.

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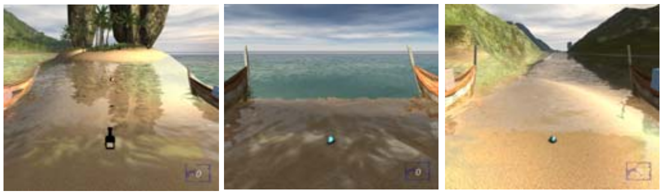

Figure 2. Three scenario environments

Figure 3. Different scenario phases with textual and graphical questions

E. 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, initial quiz level etc.) gives the user a sense of control and engagement in the task.

Environmental sounds reflect the presence of naturally occurring events and noises that one would expect on a tropical island such as birds, water, trees and wind. These sounds occur randomly, and some of them are linked to visual events.

The user can, in advance, choose among different types of music (rock, pop, folk music, classical, instrumental), depending on his or her preferences and mood, which gives the user a more pleasant experience in the game. Professionals in the mentioned types of music classified an adequate selection of accentuation, tempo, and rhythmic articulation for us according to [11, 12] in a way belonging to four quadrants of arousal-valence space. The user-selected music can belong to some quadrant, or the file can be automatically picked according to some variable in the River scenario.

Additional verbal comments, instructions or encouraging statements continuously stimulate the user to strive for better performance while exercising, compliment a successfully completed task or reassure the player when performance is poor. If haptic support is enabled, the game scenario will also provide directional instructions to the player. With respect to current hand position and desired target position, a background voice will guide the player by instructing him/her which direction to move the hand (Figure 4) and when to release the object to successfully complete the task.

F. Haptic modality

The river task includes a haptic environment that consists of haptic objects, detection of collisions between objects and different force generation algorithms. The perception of this environment is enabled via the HapticMaster's mechanism. Control is done with the xPC Target™(The MathWorks, Inc.) host-target environment that enables the connection of models to physical systems and their execution in real time. The loop executes at 2500 Hz.

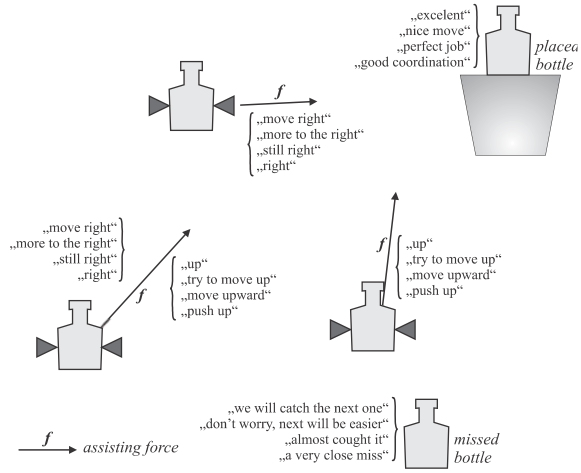

Figure 4. Verbal instructions, picked by an adaptive algorithm, are used for user encouragement in various stages of the movement task

The haptic objects in the scenario are the bottle, two baskets, the river. Included are different options for robot-assistance. The end-effector of the haptic interface is modeled as a point and represents a haptic interaction point in the virtual environment. The size of the bottle, the weight of the bottle, the speed of the bottle, the height of the baskets and positions of the baskets can be modified during the task. The presence of the water is simulated by a viscosity when the subject lowers the end-effector below water level. The river scenario includes different options of robot-assistance:

- *Catching assistance.* For subjects unable to independently reach toward the bottle, the catching assistance is available. It is realized as an impedance spring-damper system with a stiffness k and viscous friction B that moves the subject's arm in a frontal plane. The assistance generates the forces when the bottle reaches the center of the workspace, increasing when the bottle is getting closer to the robot end-effector. Vector $\boldsymbol{F}$ is the computed force. Vector $\boldsymbol{p}_{xz}$ is forward-backward and $\boldsymbol{p}_{by}$ is left-right deviance of the end-effector from the catching point. Vector $\boldsymbol{v}_{xz}$ marks the velocity of the end-effector.

$$\boldsymbol{F} = (1 - \boldsymbol{p_{by}})(k_c \boldsymbol{p_{xz}} - b_c \boldsymbol{v}_{xz}) \qquad (1)$$

- *Grasping assistance.* For subjects that are unable to perform manual grasping, the grasping assistance causes the bottle to stick to the virtual gripper. Additionally, the bottle is dropped when the subject reaches the basket. If grasping assistance is disabled, the grasping force produced by the subject needs to be higher than a minimal grasping force. The reference force can be changed during the task according to subject's grasping ability.

- *Tunnel assistance.* The haptic trajectory tunnel enables movement from the point where the bottle is caught to the point where the point is dropped into the basket along an invisible trajectory in a virtual haptic environment. An impedance controller generates a force field that allows only small deviations tangentially from the central trajectory. The control points are approximated by using B-splines from trajectories measured in healthy subjects' movements. DeBoor's algorithm enables fast calculation and is numerically stable [13]. The guidance assistance provides as well a force in the direction of the haptic trajectory tunnel with impedance controller leading the subject's arm along the desired trajectory. The *Tunnel assistance* and *Adaptive haptic assistance* are two exclusive tools, only one can be used at once.

- *Adaptive haptic assistance.* It has been shown that, when moving the hand between two points, a healthy person tends to follow a straight line, minimizing the movement jerk.

  Often, the patients cannot exert such optimal movement due to muscle coordination impairment. Instead, they might generate voluntary movement towards the target by following the path that meets their muscle coordination capabilities. Therefore, to allow the patient to arbitrarily select the most comfortable movement trajectory, the feedback controller should support the movement of the patient's hand towards the target without predefining the trajectory while the maximal time allowed is predefined.

  The controller implemented in this section is built on work by [14] and focuses on point-to-point reaching movement. Given the starting and target positions, the optimal time course is determined by minimizing the cost function. The result is a time-based trajectory, which only determines the optimal distance and velocity to the target at certain time, but not the actual reference hand position (Figure 5). The same result may be obtained by using the following feedback controller, which brings the hand to the target along a minimal-jerk trajectory.

  The actual movement of the patient's hand is compared to the optimal path. Then, the supporting force/torque on the hand is determined based on the error between the reference and the actual distance to the target.

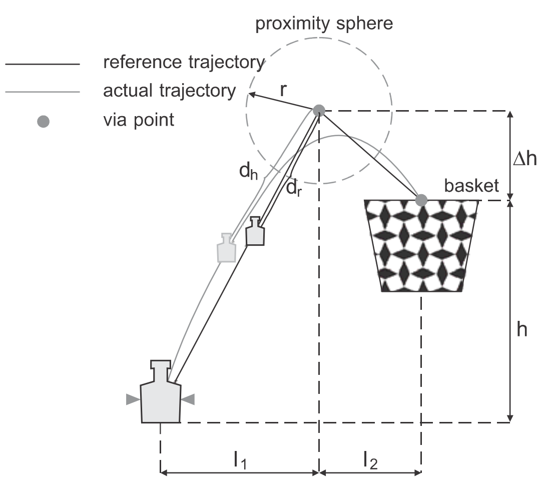

Figure 5. The adaptive haptic support system allows the user to deviate from a reference trajectory and acts only when the user is outside a certain optimal area.

  The supporting force provided by the robot is adaptive in the sense that the impedance gain in a feedback loop is based on the error between the reference and the actual distances to the target adjusts the support force according to the patient's performance. When the patient performs well a decrease of the controller stiffness is introduced. If the patient performs well, currently selected completion time may become longer as necessary leading to a decrease in the user's motivation. To motivate the user and to gradually stimulate the users to increase voluntary effort, the desired completion time is computed as the average of the completion times. In this way, the controller uses self-adjustment to completely meet a particular user's performance capabilities.

III. Clinical evaluation

A. First clinical evaluation

First clinical evaluation of the scenario was aimed at assessment of 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 6 females (age 46.2 ± 13.4 years, age range 22–61 years). They were diagnosed with intracerebral hemorrhage (5 subjects) or cerebral infarction (11 subjects). As a result of the stroke, eleven suffered from hemiparesis of the left side of the body and five suffered from hemiparesis of the right side of the body. Time between stroke onset and the experiment session was 128 ± 64 days. All were cognitively intact and only moderately physically impaired.

Upon arrival, subjects were informed of the purpose and procedure of the experiment, then signed a consent form. Then, they were seated in front of the HapticMaster, and the affected arm was strapped to the device. The river scenario was demonstrated, and subjects exercised with it for six minutes for basic accomodation. The Intrinsic Motivation Inventory (IMI) questionnaire was presented in order to evaluate subjects' opinion on the scenario, and an informal interview was conducted regarding the impression.

The IMI is a questionnaire that has been used to assess patient motivation in a variety of settings, including motor rehabilitation [5]. 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, results of the IMI showed a favorable response to the river scenario on all subscales. This shows that the river 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.

Table 1 Intrinsic Motivation Inventory results during the first clinical evaluation, 10 male and 6 female subacute stroke patients.

	max 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

B. Second clinical evaluation

Having found that the river scenario is highly motivating for patients, we wished to see if this motivation is caused by the elements of river scenario, or whether it 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 river scenario and two with an apple-picking scenario. The second is a simple scenario consisting only in picking up apples from the ground and placing them into a basket [15]. Sessions were held twice a week (once with one scenario, once with the other) for two weeks. The session was led by a 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 her own professional opinion. The IMI was filled out after each session. After the last session, subjects received an additional questionnaire asking them to express their preferences regarding the scenario/s including specific features of the river 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-minutes 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 [5], was found to be rather complicated for patients, especially statements including a negative statements. For instance, 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'. Thus, the IMI may be in future better clarified. Four out of six subjects strongly preferred the river scenario, one had no preference, and one (who had trouble comprehending the questions posed in the river scenario) preferred the apple scenario (Figure 6). Results from some of the other questions posed in the final questionnaire are illustrated in Figure 7. 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, river type scenario may not be suitable for cognitively impaired subjects.

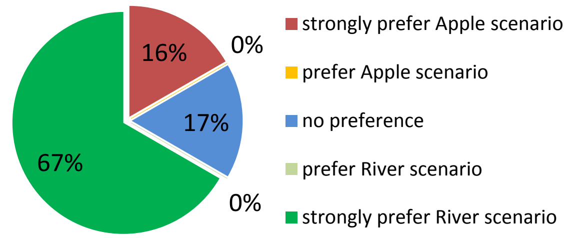

Figure 6. Patients' scenario preferences, see text for explanation.

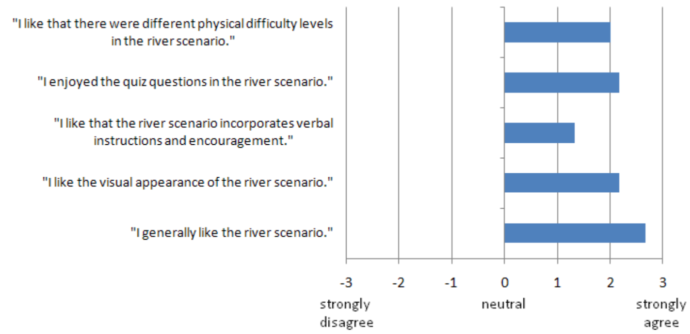

Figure 7. Subject's responses to the final motivation questionnaire. Mean values for responses of 6 subcute patients are shown.

IV. Discussion

Clinical evaluations showed that subjects enjoyed exercising with our river scenario. Even if the IMI did not show significant differences between the river scenario and the less complex apples scenario, subjects emphasized their liking of the new river 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/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 comprised only a few therapy sessions per patient, we already discovered that scenarios, which are too cognitively demanding, can actually confuse the patient. This was evident with the patient who preferred the apple scenario to the river scenario, since he had troubles comprehending the quiz questions. Based on this information, we developed the second version of the scenario where the questions are graphically represented (Figure 1 and Figure 3 middle and right). 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 quiz 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, the participants 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 the 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). Different types of music could perhaps even affect performance by relaxing or energizing the patient. A step toward optimizing the scenario would be to evaluate the effect each element has on each patient and thus to decide whether the corresponding element 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 river scenario seems less beneficial since they need to focus on the movement itself and do not need additional cognitive challenges.

Appropriate measures should be considered for the purpose of evaluating patient motivation. The IMI, though previously used in rehabilitation, may not be entirely appropriate, since some patients have trouble answering the questions, resulting in skewed results. Simpler questionnaires or other methods such as therapists' evaluations or psychophysiological measures could be considered instead.

Activities of daily living (ADL) scenarios often include pick and place movements with grasping, which are also included in presented scenario. In addition to simple ADL tasks, the River scenario offers a pool of additional cognitive challenges that could eventually make the trainee to work harder and longer.

V. Conclusions

Whole range of needs that have diverse rehabilitation robotics users, require whole range of application scenarios. Multimodal river scenario uses a number of different visual, audio and haptic solutions to increase motivation of the user. In particular haptic, tunel, catching and grasping assistance are more beneficial to severely impaired persons, while combinations of audio, video and haptic challenges are more attractive for less impaired. The multimodal elements utilized here in upper extremity are suitable for implementation in exercise environments for different body parts. The combination of motor and cognitive challenges in River scenario is completely new and to our knowledge has not been previously used in any robotic rehabilitation device scenario. Locomat rehabilitation scenario for lower extremity exercise has recently followed the principles presented here.

The next step forward is use of river environment for biocooperative closed loop control. By measuring performance, biomechanical and psychophysiological parameters online, and subsequently changing the haptic, visual and audio cues for bio-feedback, the adaptive challenge or motivation can be provided to patients during the physical therapy exercises. This has already been implemented and will be published in a sequence.

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