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Virtual Reality in Neurorehabilitation: Mental Rotation

M. Marusan[1], P. Kulistak[2], J. Zara[1]

[1] Czech Technical University in Prague [2] Dept. of Neurology, Faculty Thomayer's Hospital, Prague, Army Rehabilitation Center, Slapy nad Vltavou

Abstract

This paper describes a Virtual Reality (VR) application for neurorehabilitation of patients following traumatic brain injuries (TBI). The application is based on mental rotation tasks frequently used to describe different human mental abilities and initial assessment of consequences of TBI. This paper is an extension of standard mental rotation paradigm by Shepard & Metzler, and Vandenberg & Kuse test according to recent knowledge of modern neuropsychology approaches. The application has been designed with the aim to meet various users' wills, so the rehabilitation can take place anywhere and anytime. The implementation is independent on special equipment as 3D glasses or special gloves or suit, or special medical tool (special-shaped joystick, adapted keyboard or controls) in order to be most accessible for most users. In these terms, of course, users depending on these special equipments are not considered.

Categories and Subject Descriptors (according to ACM CCS) I.3.7 [Three-Dimensional Graphics and Realism]: Virtual Reality, J.3 [Life and Medical Sciences]: Health

1 Introduction

Mental imagery is one of the most fascinating processes in brain. The process is defined as "mental representations of physical objects or events that are no longer present" [GOO05]. The results of mental imagery are mostly mental images, i.e. not existing images of objects and scenes in present reality.

The ability to use mental images plays an important role in everyday skills, such as finding possessions and negotiating routes, and during performance of cognitive tasks, such as memory, reasoning and problem solving [KOS94].

However, mental imagery is not a one, indivisible process, but consists of several component processes. The Evidences from neuropsychological [KvK90], developmental [DK94, KMB90] and experimental laboratory [KBC84] studies suggest a distinction between:

- image generation (the ability to form mental images),
- image maintenance (the ability to retain images over time),
- image scanning (the ability to shift one's attention over an imaged object), and
- image manipulation (the ability to rotate or otherwise transform images).

According to Kosslyn [DK94], image generation can be further subdivided into two phases. First, a representation of the to-be-imaged object is activated in long-term memory (image activation). Second, the image is composed sequentially, segment by segment (image composition).

In this paper we focus on the image manipulation part of using mental images, especially rotation of mental images. Our task was to create an application that can be used for neurorehabilitation of patient suffering from the traumatic brain injuries (TBI). Such application is based on special mental tasks described further with use of modern technologies such as VR environment.

The secondary goal was to create this application to be easy-to-reach (at home, on users' own computers) by patients using standard tools (computer mouse, keyboard). Moreover, rehabilitation results have to be retained for further utilization and easy-to-recollect as well.

Section 2 describes the mental rotation term and use of this phenomenon in neurorehabilitation. Section 3 discusses a use of virtual reality in neurorehabilitation. A design of our VR application is described in section 4, implementation details are shown in section 5. Section 6 describes experiments with the application.

2 Theoretical Background: Mental Rotation

One of the experimental paradigms used for testing mental image representation is the mental rotation paradigm. Shepard and Metzler [SM71], in their classical psychological study, found that the time it takes humans to distinguish between the image (model) and mirror-image (image) of rotated figures is linearly dependent on the angular disparity between the figures, i.e. there is a kind of continual proportion between the angle of disparity of the model and its image and response time (see Figure 1).

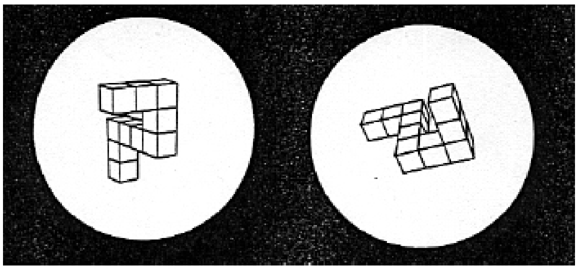

Figure 1: *Shepard and Metzler test - original object (left) and its another image (right) [SM71]*

It was argued that the subjects use an image-like mental representation in a time-consuming, analogue transformation process of visual information which Shepard and Metzler [SM71] called *mental rotation*. It is assumed that the imagination of a rotating object is equivalent to the perception of the physical rotation of a real object [SC82]. Moreover, the same neural process can be involved both in the generation of imagined motion and in the perception of motion of existing objects [CM82, JC92].

During the time, more studies were made to support these conclusions [TR04, RBR05, and PEW05] and improvements in testing were made in [VK78] where not only the model and its image were presented but also a set of several possible (false) images differently rotated with just one correct image included.

Mental rotation tasks and studies of this phenomena become the base for exploring and researching of theories about sex differences in spatial transformation tasks [PLL95], where males were found to have better results than female testers [PLL95], age differences [KN05, WLH04] or differences between right- and left-handed humans [COR97].

Furthermore, studies for 3D user interface development were also made on the mental rotation tests basis [RGS05, RPM05]. Thus, not only the medical science is involved in metal rotation testing and research.

Another research field based on mental imaging, thus rotation of mental images, is brain damage rehabilitation [RBR05, TR04]. It has been shown which portions of human brain take part in mental rotation tasks [PEW05, ZRG99]. The differences between left and right hemispheres were discussed [TR04], thus more evidences were found that the ability of mental rotation is decreased by brain injuries (as lesions of parietal lobe).

The traumatic brain injuries (TBI), often reported as "silent epidemic" [RJ94], can be caused by many factors, as neurodegenerative diseases, stroke cases, or injuries (car accidents, etc.). It is estimated that only stroke cases in Western Europe indicate an incidence of 250 per 100,000, with an even higher incidence in Eastern European countries [BBB00]. Incidence of TBI is increasing with age, due to the neurodegenerative diseases and could increase even higher with counts of automobile accidents as if they are considered as main causes of TBI for adults from 20 to 40 years.

Brain damage rehabilitation has short history unlike other neural techniques, thus it is not very well supported by clearly defined and agreed theoretical base [RBR05]. However, some principles yet have been established and form the basis for other researches by defining a vision of what mental rehabilitation should seek to achieve. It is emerging that the rehabilitation approach has to move away from strict medical model of TBI to more complex view of patient suffered from TBI and surrounding environment.

3 Virtual Reality in Neurorehabilitation

At this stage, other science branches come in useful and participate on developing more efficient instruments and approaches for neurorehabilitation as a part of treatment of TBI. Especially computer science with the use of modern computer graphics, virtual reality, and visualization has a great potential to reduce significant amount of TBI consequences.

Virtual reality (VR) has already proved its potential to help in many different areas of brain disorder: fear reduction of phobic clients [HRW96, CHW97], pain reduction for burn patients [HOF97], navigation and spatial training in children with motor impairments [ILL97], functional skills in persons with developmental disabilities and autism [BS96], and in the assessment (and in some cases, rehabilitation) of memory [ABR96].

Rehabilitation and TBI impact treatment with the assistance of VR and primarily based on mental rotation are to be found in studies of spatial skills [RBN98], and executive cognitive functions [PMA98] where are mostly combined with standard “paper” versions of Shepard and Metzler and Vandenberg and Kuse tests.

However, fully-immersive version of VR (head mounted displays, gloves, etc.) is not the only possible way of neurorehabilitation [RAB98]. According to cost/benefit issues for mental health application [RWB98] the non-immersive VR versions based on standard desktop computers can be efficiently applied. The later approach was used in our application.

4 Our Approach

Our aim was to create a neurorehabilitation program based on standard web application with all benefits that this implementation can offer. First, the application users – patients – are not bounded with their medical centre facility; on the contrary, they are able to practice rehabilitation tasks at home at any time. Second, the application is implemented to be independent on special equipment as 3D glasses, joysticks, etc. and so that there are minimal purchase costs. Further, the application is fully remotely administrable and thus can be managed and adjusted to specific needs.

4.1 Neurorehabilitation Application Core

The program is based on the Shepard and Metzler mental rotation tasks – rotation of 3D objects. In our application, two images of the same 3D object are presented to the user – they are called *model* and *image*. The model is rotated from the initial pose to another position (given by the current test settings – scenario), then a new image is rendered, see Figure 2.

The task for the user is to rotate the image object into the same position as the model. This has to be fulfilled in specific time limit. The task ends when the user sets the image into appropriate position and confirms that by pressing a check button. This avoids randomly achieved correct positions that could appear by continuous manipulation with the image object. Moreover, the number of inquiries of the check button is also counted and evaluated. The monitored quantities of the tests are the resulting time and number of checks to the right position.

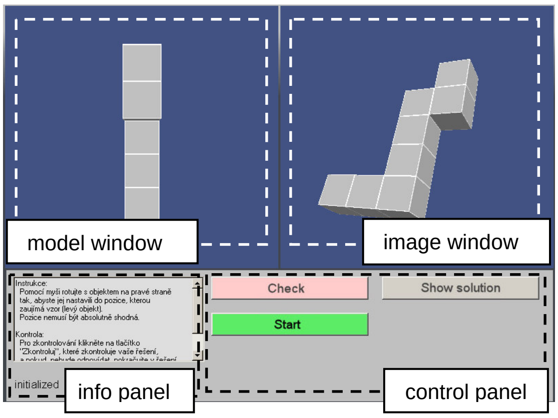

Figure 2: *Application layout shows the distribution of user interface elements on the screen in the patient test mode*

These tests are embedded into standard web application which can be divided into several functional parts as described in the following text.

4.2 Patient Test Part

The primary function of the application is the rehabilitation of users – patients – following TBI. This part includes not only the test itself but also time measurement and position check counting.

The application is designed according to the most simple and user-friendly user interface requirement. Two large dominating windows may attract most of user's attention (Figure 2). Big control panel bellow contains only necessary control buttons with simple commands to handle test progress – start, check, and show solution.

Simplified test instructions are displayed in the left bottom part of the control panel since the patients have to be repetitively given test assignment due to their possible brain disorder.

Furthermore, task progress and short additional information are shown on the bottom line to inform users about test state or actions being performed, e.g. preparing arrangement, wrong solution, right solution, etc.

Any other information or controls would be undesirable and would just disturb users and decrease their attention necessary for performing rehabilitation tests.

4.3 Test Preparation Part

To accommodate up-to-date needs of modern neuro-medicine, such application cannot be designed in an inflexible structure with predefined and final accessories. On the contrary, it has to be a flexible instrument that can be simply modified to fulfil present specific needs.

Following from this point, the doctors can manage all test settings for the best fit to patients needs. They can change the initial rotation of the object and thus sensitively adjust the difficulty level. For this purpose, the rotation can be either set as the compound of rotation in every axis (x, y, z) or doctors can switch to interactive mode in which the initial position can be tuned by direct rotation of the given 3D object. The test time and the number of inquiries to the right position can also be set in compliance with specific needs.

Next feature is the possibility of choosing the object of mental rotation. So far we have prepared up to 24 predefined objects. Further objects can be simply added by uploading appropriate 3D models in VRML format into application database.

Tests are grouped into bigger logical units called "test schedule". The schedule is a set of tests with different settings. Afterwards, the schedule can be assigned to the patient's rehabilitation program.

4.4 Administration Part

The integral component of the application is the administration module for managing user accounts (doctors, patients) and test result viewing.

This part offers standard methods to handle user accounts – add user, remove user, assign patient to a doctor (tree hierarchy), etc. It also contains an interface for viewing users' details and program progress with graphic representation of results in form of graph. This is important for further data processing in order to predict success of treatment.

5 Implementation Details

The application is designed as a standard web application based on the client-server architecture. Client side is represented by Java applet connected with two VRML browser windows. The web server utilizes both file systems and a database for storing 3D objects, tests, patient records, and other related data (see Figure 3).

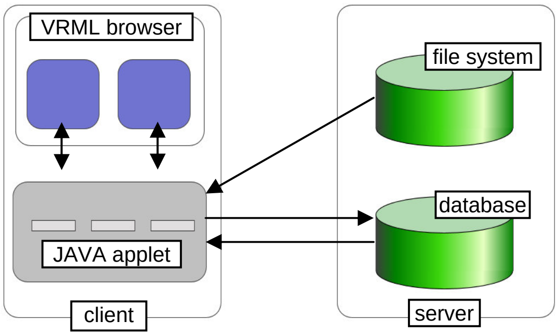

Figure 3: *Application architecture – data transfer between client and server*

5.1 User roles

Users are divided into three groups and form a hierarchy: Administrator, Doctor and Patient. Every user has own account which determines the user role, and thus the user rights within the application.

The Patient has access only to the test schedule (and then to individual tests) assigned by the doctor, to the results, and to testing area.

The Doctor can manage Patients' accounts. This includes adding, removing, editing, assigning to another account. The Doctor also creates and modifies rehabilitation tests and the whole test schedules – creates new, assigns to Patient, etc. – so that the Doctor manages the overall rehabilitation progress.

Administrator is at the top of the hierarchy doing administrative actions, system maintenance, and improvements.

The user record consists of the following items to best fit the medical needs: name and surname, sex, health condition flag (whether the user is healthy or sick), note (used for simple diagnosis of patient), parent (nursing doctor).

5.2 Application Structure

The interaction between user and scene is provided by events that are caught by Java applet and processed there. Every necessary action as reaction to the transformation changes is processed in Java and appropriate results are sent back to the scene or are displayed in Java Applet Control Panel or other action take place there (e.g. altering database information or loading data), see Figure 3.

Two scenes/objects are displayed in the application frame: one for the model and one for the image object. Both scenes serve as containers for specific object. A fragment of the source code for such a container is in Figure 4. The objects of mental rotation tasks are dynamically loaded in both scenes (Figure 4, line 9). The object to be loaded is determined by user test results: either a new object (test configuration) is requested after a successful test performed or the current test has to be repeated.

```
 1 Group {
 2  children [
 3   DEF SCENE_SENSOR SphereSensor {...}
 4   DEF SCENE_ROTATION Transform {
 5     children [
 6      DEF OBJECT_ROTATION Transform {
 7       children [
 8        DEF OBJECT Inline {
 9         url [""]
10        }]   }]}]
11 }
```

Figure 4: *Simplified code of VRML object container*

Line 3 shows a global SphereSensor node assigned to every modelled object loaded into Inline node (line 9). This kind of sensor allows a continuous rotation of the object around arbitrary axis.

However, due to the user disabilities, the continuous movement of rotated object is not considered as convenient. Hence the smooth rotation should be replaced by a sequence of discrete steps. This allows the users to achieve better accuracy when trying to set the object into appropriate position.

To generate appropriate discrete rotational steps, we have implemented a function written in Javascript and included directly in the VRML scene. This function takes the rotation value coming from the SphereSensor node as the input and adjusts it to a value representing a discrete step. A computation is done by multiplication of each rotation vector component by the step coefficient:

$$R[i] = \text{Math.round}(R[i]*q_s)/q_s,$$

where $R[i]$ is the rotation vector component, q_s is a step coefficient. The q_s coefficient was experimentally adjusted to 0.1. This value makes the rotation easier according to user abilities but is not too big to generate unexpected jumps and results.

Objects loaded into container do not need to have additional code for handling interactive events; i.e. any static VRML model (correctly modelled) can be used as object-image in this application. This approach gives a lot of possibilities to the application administrators (doctors) to test their patients using arbitrary shaped and complex objects.

According to the first usability tests on the rehabilitation application another advantage is given to the patients: for correct solution of the test the objects do not have to be precisely in the same position – a small position clearance is allowed. The clearance coefficient has been also obtained experimentally. Its value is 0.2 radians in each axis of rotation.

VRML language represents any rotation using an "axis-angle" composite vector - object is rotated by given angle in radians around the specified axis – see Figure 5. In order to compare if two objects have the same rotation with small clearance in every axis, we convert the axis-angle vector for example into Euler representation and then perform the comparison.

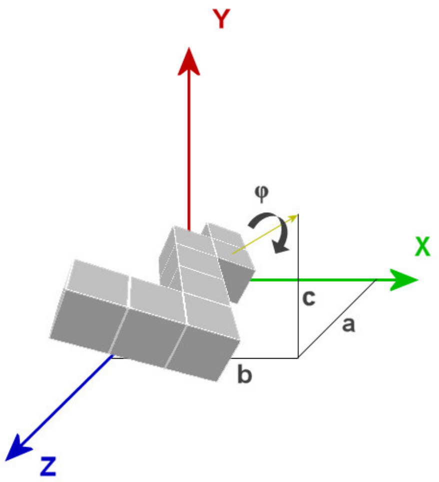

Figure 5: *Axis-angle rotation representation*

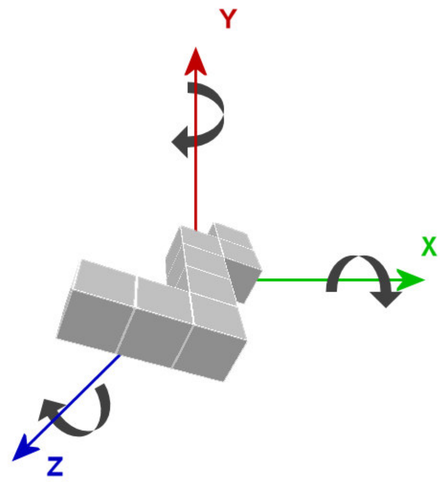

Figure 6: *Euler angles rotation representation*

The Euler representation is determined as a composition of partial rotations around each axis (see Figure 6). The conversion between these two representations is done through quaternion representation [BAK06].

Once we have both rotation vectors (model and image) converted into the Euler representation, we compare both rotations axis by axis and according to the result, we make a decision whether the solution is correct or not:

$$|\varphi_M[i] - \varphi_I[i]| < q_c,$$

where $\varphi_M[i]$, $\varphi_I[i]$ is angle (in radians) in Euler representation of model object and image object, and q_c is the step coefficient.

5.3 Technical requirements

The required software configuration is Microsoft Windows and MS Internet Explorer with ParalellGraphics Cortona VRML browser plug-in installed. Microsoft Java Virtual Machine to support the applet communication and Javascript have to be enabled for scripting.

The Java applet, which provides control and interaction with VRML worlds and the database on the server side, uses obsolete Java classes which are no longer supported by Java Sun JRE so that MS Java VM is required. Due to this limitation, MS IE is required, because other web browsers do not support MS Java VM.

6 Experiments

Thirteen subjects - 8 females and 5 males - in the age from 25 to 50 participated in first tests (those who have not finished or give it up before end are not considered). Subjects were mainly educated at university degree. Five of them have some TBI diagnosis.

The subjects were given specially created mental rotation tasks in four schedules, each consisted of 5 – 20 tests.

First group of test, first test schedule, consists of six simple tasks with 3D objects (cubes or spheres with protrusions) randomly rotated into the initial position. The main purpose of this first set was only to accommodate users to the application interface and make the users to be familiar with the elements of application control (Control Panel, interaction with mouse, etc.).

The second test schedule consists of 12 mental rotation task with standard cube-shaped 3D objects, similar to ones used by Shepard & Metzler. Every task had to be repeated for the five times in order to be marked as completed and to allow users to step forward trough the plan to following task.

The angle of initial rotation of the model object increased in every step forward trough the Plan. This might simulate the increasing level of complexity

The next, third, Plan consists of five mental rotation tasks. These were made of “real-life” object as sofa, table, lamp etc. Since the task was still the same as with the standard cube-shaped 3D objects, the purpose of this Plan was to show differences, if any, between performing mental rotation task with these two different sorts of tests. Another purpose was to make the rehabilitation more attractive for the users and increase their attention and stimulate motivation.

First experiments pointed out the drawback of application user interface – it had to be simplified and visible instructions of each test had to be added. Next, certain time to familiarize with application handling – especially with standard PC mouse-driven rotation – was necessary.

In spite of the fact that such number of subjects tested so far has no significant statistic importance the first results show tendencies in which the further experiments and development should be aimed.

7 Conclusion

Rehabilitation programs for brain injured persons (including patients with cerebrovascular incidents, traumatic injury, tumor among others) seem to be geared toward the recovery of physical abilities. In such settings, cognitive disabilities may be largely overlooked. Frequently, the criterion for admission or discharge is based upon the patient's ability to walk and talk. Many patients ant their families remain unaware of cognitive problems themselves until the patient attempts to return to school or work.

Deficit of visuospatial ability is one of impairments. Everyday life situations, which rely on this ability to use imagery to turn over or manipulate objects mentally, are quite common. These include automobile driving judgments, organizing items in limited storage space, sports activities, and many other situations where one needs to visualize the movement and ultimate location of physical objects in 3D space. Mathematical performance has been linked to mental rotation ability. Spatial orientation abilities have been shown to be an important variable in the differential diagnosis of dementia (e.g. Alzheimer's disease).

The first step in any rehabilitation process is an appraisal of the patient's current functional profile. Conventional "paper and pencil" neuropsychological tests of cognitive functions have been criticized as lacking "ecological validity". Here are advantages in virtual tests of cognitive functions, which allowing us to estimate a patient's probable cognitive level in a real life situation.

In addition, repetitive training of spatial abilities can play significant role in effects of treatment after TBI. Especially, this application gives patients the possibility to continue in initiated rehabilitation by training of cognitive functions after allowing from rehabilitation centre. It is also important to keep motivation – keep mental activity – of the patients that can be prone to apathy and depression.

This application can serve as a helpful complement of a TBI treatment, especially for the rehabilitation and training after hospitalization in special medical centre. We expect that further experiments and testing will proof and even extent our conclusions.

8 Acknowledgements

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