DESIGN OF A VIRTUAL REALITY SUPPORTED TEST FOR SPATIAL ABILITIES

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ABSTRACT: This paper focuses on the development of a new spatial ability test in virtual reality (VR). This test measures the ability to visualize and mentally manipulate three-dimensional objects directly in 3D space, and should thus have a higher ecological validity than previous spatial ability tests. Items are viewed through head mounted displays and manipulated by means of a wireless pen input device. As a dynamic tests consisting of a pretest, a training phase, and a posttest it does not only measure a person's current status but also his or her learning potential. Monitoring user interactions in a VR environment allows to measure test performance in ways not possible with traditional means. We describe design and development of the test and will present results of a pre-study with 240 participants conducted in early 2008.

Keywords: Spatial Abilities, Virtual Reality, Dynamic Testing.

1. INTRODUCTION

In a previous research project the main authors evaluated the effects of an augmented reality (AR) based geometry training on spatial abilities [5, 8, 15]. Two results were surprising and intriguing: (1) Classical paper-pencil spatial ability tests seemed to be not sensitive to some aspects of spatial performance, possibly due to their two-dimensional nature and limited difficulty range, and (2) in the control group (without any training), there were marked individual differences in performance increases between pre- and posttest. This suggests that individuals differ in their "learning potential" with respect to spatial abilities. These findings led us to the idea of developing a new spatial ability test that (a) measures spatial abilities in three-dimensional space, and (b) includes a training phase, so that learning potential as well as performance status can be measured.

The main goal of our current work whose initial findings are presented here is to develop a new means of measuring spatial abilities in an ecologically valid way. The most important innovation is that our measurement instrument is based on virtual reality, a technology that allows for the projection of virtual objects into real space. Wearing head mounted displays users can interact with three-dimensional objects in space. They can view them from different perspectives and construct or manipulate (e.g., intersect, transform or rotate) them. Thus, virtual reality offers possibilities far beyond those of classical spatial ability assessments. Spatial ability by definition mostly deals with objects and configurations in three-dimensional space. Previous spatial ability assessments, be they paper-pencil tests or computerized versions, are two- dimensional in nature and therefore require transformational processes that many real-life spatial tasks do not demand. The virtual three-dimensional stimulus material that we are developing is one important step closer to reality. Testees see the test items three-dimensionally and can view them from different perspectives (Figure 1).

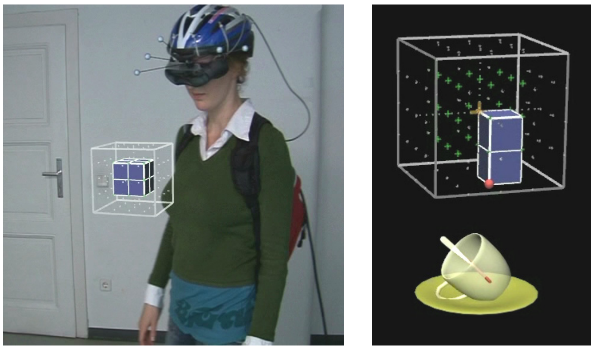

Figure 1: Left: Participant walks around a test item which appears fixed in space. Right: An animation shows a yellow cup rotating around a horizontal axis. It indicates that the test item must mentally be rotated the same way.

The construct validity of the test for measuring three-dimensional spatial ability is expected to be higher than that of existing tests. The new item material requires participants to visualize and reconstruct rotations of three-dimensional objects in space. Items can be designed to span a wide range of item difficulties (see 3.2).

2. RELATED WORK

2.1 Spatial Abilities and Spatial Ability Tests

Broadly spoken, spatial ability refers to the ability to mentally represent and manipulate visual-spatial information. Spatial ability is not a unitary concept but includes several heterogeneous "sub-abilities", each referring to different aspects. Various attempts have been undertaken to structure spatial ability into sub domains [2, 17, 27]. Most of these proposed structures focused on relationships and similarities among spatial tests and were based on the results of correlational and factor-analytical studies. The most-cited and widely accepted model was proposed by Lohman [17], who distinguished three sub factors of spatial ability: Spatial Relations (or Speeded Rotation), Visualization, and Spatial Orientation. Spatial Relations refers to highly speeded tasks requiring the mental rotation of simple two-dimensional [28, 17] or three-dimensional [25] objects. Visualization includes a broad spectrum of complex, multi-step spatial tasks that are administered under relatively unspeeded conditions. The majority of spatial ability tests (e.g. paper folding, form board, or surface development tests) are assigned to this sub dimension. Spatial Orientation refers to tasks in which a given object or an array of objects has to be imagined from another perspective [11]. This dimension is related to orientation and navigation in real or virtual environments ("large-scale spatial abilities"), whereas the former two refer to manipulating three-dimensional objects, such as constructing or visualizing mechanical objects ("small-scale spatial abilities"). An overview and classification of spatial ability tests is given by Eliot [6]. Interestingly, most stimulus types used in current spatial ability tests are still very close to Thurstone's original developments.

There are several shortcomings of traditional paper-pencil formats that are especially relevant when spatial ability is concerned, and some authors have argued that these may be one reason for the relatively low predictive power of spatial ability tests when it comes to real-life spatial tasks [10, 20, 13]. First of all, although most existing spatial ability tests – especially the more complex ones – aim at assessing three-dimensional spatial abilities, virtually all of them use two-dimensional presentations of the stimulus material. Thus, solving these test items requires participants to mentally transform a two-dimensional picture into a three-dimensional figure, to perform some mental manipulations on the figure, and to re-transform the result into a two-dimensional picture. One could argue that this 2D-3D transformation adds a difficulty facet that is not directly related to what is supposed to be measured.

A second shortcoming is that the large majority of existing tests require participants to select the correct solution to each item from a (small) number of response alternatives. Thus participants can solve tests by excluding the alternatives one by one, often by concentrating on single features, as opposed to mentally constructing the correct solution [7]. There are several possibilities for avoiding this problem. One is to have participants actively construct their solutions [18], which is facilitated by the use of computerized systems. Another is to present the task in a stepwise fashion so that participants need to keep track of a sequence of manipulations. In such cases, participants need to mentally manipulate at least parts of the stimulus in order to be able to identify the correct solution.

These two points of critique are true not only for paper-pencil, but also for the majority of computerized tests. Most computerized spatial ability tests that are currently available are simply computerized versions of existing paper-pencil tests [20] - see also overviews of available computerized tests e.g. [24].

New technologies such as virtual and augmented reality allow for the development of a new generation of spatial tasks that are three-dimensional in presentation and response format, and support active construction of solutions in three-dimensional space.

2.2 Applications of VR/AR for Testing Spatial Abilities

As early as the 1980s, some authors used computers to develop non-static spatial tasks involving moving stimuli [1, 13, 20]; an approach which seems to be currently rediscovered e.g. [3].

There are only few applications of virtual or augmented reality for testing spatial abilities so far. One is the Virtual Reality Spatial Rotation (VRSR) System [22]. Within this system a virtual version of the Mental Rotation Test (MRT) [29] was developed in which participants can physically rotate the stimulus material. Findings obtained with this test, which was intended for clinical use, show interesting differences to the standard MRT. The correlation between performance in the classical and the virtual MRT is only about 0.50. While gender differences favouring male participants are virtually always found with the standard version [30] no gender differences were found with the virtual version [19]. Recently a virtual version of the Mental Cutting Test was presented as well [12].

A number of studies have investigated orientation and navigation in virtual environments through which participants navigate using joysticks or other devices [9, 4, 31]. These applications have shown to be very fruitful for studying orientation processes; however they are still restricted to an essentially non-spatial format of presentation. Participants see the environment on a screen and many important cues that are automatically encoded during real-life locomotion in an environment are missing [26, 16]. The type of virtual-reality application that we are developing overcomes this problem. Participants can move around the objects they are working on and can virtually "touch" and manipulate them. Compared to the use of real three-dimensional objects, VR systems allow for the free creation of an unlimited number of objects and manipulations can be easily undone and redone.

3. DSTAR - SPATIAL ABILITY TEST

3.1 Technical Setup

The standard immersive setup used for our Dynamic Spatial Test in Augmented Reality (DSTAR) supports one user wearing a Sony Glastron stereoscopic see-through head mounted display (HMD) (Figure 2). It provides a stereoscopic view of the virtual environment. The user interacts with the

system using a wireless pen. Position and orientation of head and pen are tracked using iotracker [21], a 4-camera infrared-optical tracking system which provides sub-millimetre accuracy. In this setup users can walk around test items to view them from different sides.
One dedicated quad-core PC is used as a tracking server which also renders the stereoscopic view for the user.

Figure 2: Outside view of a user constructing a solution. The user wears a head mounted display and uses a wireless pen as an input device.

It should be noted that we do not use the see-through feature of the HMD during test sessions; only the virtual environment can be seen. In pre-studies we observed that most inexperienced users prefer the non-see-through option. Not seeing the real world allows inexperienced users to focus and concentrate better on the task at hand. It immerses them further in the virtual environment and enhances the feeling of presence.
At the beginning of each test run the height of the test items can be adjusted to position them at a comfortable height for each person. Therefore a tracked prop is used that can be moved up and down a pole.
DSTAR is based on the Studierstube [23] AR/VR framework. It is a robust and widely used framework that provides an excellent base for developing AR/VR applications.

3.2 Test and Item Design

A new test session begins with the user watching a nine minutes instruction video that explains the DSTAR test environment. Then the actual testing in VR takes place which lasts approximately 30 minutes. When launching the test application a brief tutorial consisting of three test items starts. Tutorial items are very easy items helping the user to get familiar with the VR environment and interaction therein.
Test items in general consist of multiple simple and complex figures composed of single cubes. These figures are presented within a 4x4x4 transparent cubic grid. One such object is shown in Figure 3. The grid appears to be floating in mid space at a fixed location in the middle of the room (Figure 1 left). Items always contain several – typically two to four – steps. Each step consists of a virtual object positioned within the transparent grid plus a rotation of that object.

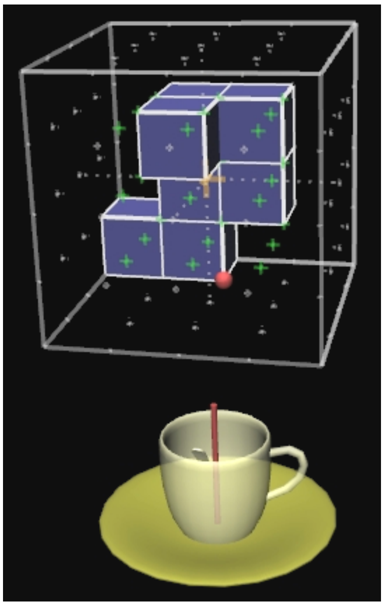

Figure 3: Complex figure as part of a test item. The red point indicates the center of rotation. The tea cup shows which rotation is performed on the given object. In this image the vertical axis is the axis of rotation.

A virtual tea cup (including handle and spoon) beneath the grid is used to demonstrate rotations. The tea cup is animated to visualize axis an angle of rotation (with the angle being 90 degrees or multiples). A non-symmetrical real life object was chosen to display rotations in an understandable way for the whole test population. Participants have to mentally rotate the figure around the given center of rotation (red dot in Figure 3) using the rotation displayed by the tea cup.

After memorizing the end position of the rotated object the user himself chooses when to advance to the next object in the sequence. There is no time limit. The subsequent object has again a (different) center of rotation with a tea cup below indicating which rotation to perform. There are usually two to four different objects/steps within an item. The positions of all mentally rotated objects have to be memorized and combined mentally. They result in a bigger connected object in the 4x4x4 grid.

In a final step this resulting object must be actively constructed by the testee inside a blank 4x4x4 grid (see Figure 4 right). This enforces mental construction of the whole solution. It avoids the strategy of excluding alternatives out of a pool of potential solutions based on specific features.

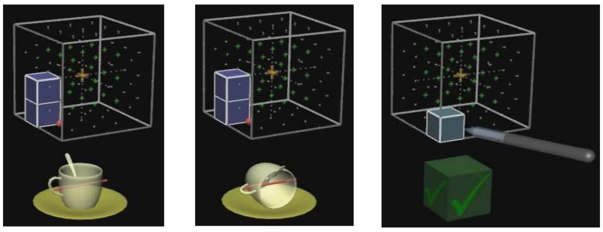

Figure 4: Left: Simple object which has to be rotated 90 degrees as indicated by the tea cup (middle). Right: Final construction of the solution in an empty grid.

Since most participants have never used a VR environment before, interaction has to be extremely intuitive. This is a major usability requirement of the test.

In order to keep the focus of the testee on the object in the center of the room, all interaction elements are arranged around that cube. All elements can be handled by using a single button on a wireless pen. When clicking the button while the pen is located at the tea cup, the animation showing the rotation is repeated. While viewing objects there are yellow arrows displayed at the left and right side of the cubic grid (Figure 5). They point to the left and right and indicate that the user can switch backwards and forwards to view previous and subsequent steps of the item. As long as the user does not choose to solve an item he can still study the whole sequence of objects (Figure 5). When entering solution mode the arrows disappear and a green checkbox appears below the cubic grid (Figure 4 right).

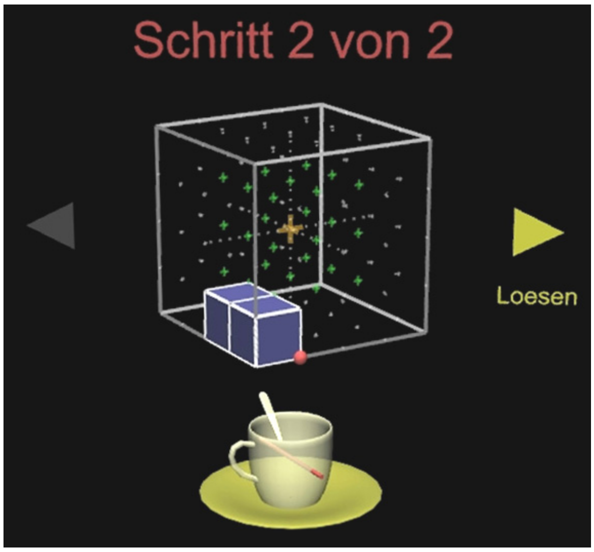

Figure 5: Entering solution mode by clicking the right arrow.

In solution mode the pen is used to draw a solution inside the empty 4x4x4 grid. Clicking the checkbox submits the constructed solution. The test item is concluded and the next item starts.

An item pool of 80 test items was generated following construction rules based on theoretical considerations. Parameters influencing the complexity of an item are "dimensionality" of the objects, rotation axes and their position, complexity of the single objects, their position within the grid, number of rotations per item and angle of rotation. Multiple rotations (two) per object are possible as well using multiple (two) tea cups below the cubic grid.

Given these parameters items are ranked in four categories: easy, medium, difficult, extreme. In chapter 4 we give details on the evaluation of items.

3.3 Advantages of using VR

One general benefit of computerized tests is that additional performance measures, e.g. response latencies and information on solution strategies, can be collected [9]. Self-report measures of strategy use can be problematic because they require a high amount of introspection [10, 8]. The non-reactive assessment of individual differences using computer logs offers a non-intrusive method of analyzing solution strategies; however, these possibilities have hardly been used yet.

Monitoring user interactions in a VR environment allows to measure test performance in ways not possible with traditional means. In addition to recording the time required to solve an item or certain steps, we monitor all user clicks when constructing a solution, (head) movement of the user around the item, number of forward/backward steps during the test and correctly solved items. All of these variables are surveyed to analyze if we can deduce strategies that the participant used to solve the tasks.

3.4 Dynamic Assessment of Spatial Abilities

Another important aspect is that we will develop a dynamic assessment of spatial ability. This is a test that measures both current performance level and potential for improvement. Dynamic tests consist of a performance (status) assessment, a training phase, and a second assessment of post-training performance. In this way, in addition to a single-time measurement of performance status, the degree to which an individual can profit from training is assessed. Previous research has shown that the potential to profit from training is important and valid additional information about a person because it levels out – at least partly – individual differences in relevant pre-assessment experience. For example women's performance deficit in spatial tasks compared to men can be linked to a lower degree of practice and may be leveled out, or at least reduced, by relatively brief trainings. In a previous project [5] we found marked increases in test performance from pretest to posttest even in the control groups, especially in participants with low pretest performance. From this perspective, assessing training profit in addition to pretest status increases the predictive power of a test.

4. EVALUATION AND RESULTS

In a pre-study 240 persons participated. Up to date we can present data of the first 152 participants (93 female, 59 male), aged 19-74 (mean 26), mainly students of cultural sciences (69.6%) and technical sciences (18.0%). The whole study is conducted in a dedicated room equipped with the specified hardware at the Alps-Adriatic University of Klagenfurt, Austria.

4.1 Pre-Study Evaluation Design

Testing included the DSTAR test consisting of six items with varying difficulty, tasks on spatial working memory and a paper-pencil standardized spatial test (3DW). Five parallel DSTAR test versions (each consisting of six items) were evaluated.

Using Item-Response-Models the validity of the theoretically based difficulty levels of the items was tested. Verbal reports concerning strategies were recorded and transcribed and after that categorized by independent coders; agreement of the category attribution between coders was high.

Since we were interested in inter-individual differences in applying strategies, participants were asked to describe the cognitive strategies they used to solve the spatial tasks in virtual reality. Our hypothesis was that individuals with high spatial abilities would use more differentiated strategies than less experienced persons.

4.2 Results

105 participants took part in a first pre-study where an initial set of 5 parallel tests with 6 items each was tested. The test duration varied between 24 (test 5) and 31 minutes (test 4) in average and also the difficulty of the parallel tests varied greatly even though they were designed to be equally challenging in theory.

Difficulty parameters of the items had an impact on the verbally reported solution strategies i.e. visualizing everyday life objects instead of complex figures, imagine a coordinate system to arrange the single cubes etc. Most persons do not explicitly begin to think consciously about solution strategies until a certain difficulty level is reached. As assumed we found varying differentiation of verbal strategy reports, depending on the number of correct solutions in the test, experience with spatial tasks, gender and educational background.

The results show expected gender differences in our test. Men solve 3,16 out of 6 items in average (σ = 1,55), women only 2,25 (σ = 1,26).

Based on the findings regarding difficulty of the parallel tests of the first study, all tests were redesigned and very difficult items were substituted by easier ones. In a second run the rest of the participants (135 persons) used the easier tests. We only have data of 38 participants of the 2nd study yet. They show that men solve 4,33 items and women 3,33 out of 6 (with similar standard deviation) in the new version.

We found evidence for strategy changes during participants' examination of the spatial tasks, but also adaptation on task difficulty by applying training experience through former test items. For example item number 4 was exactly the same in all parallel tests but the success rate of this specific item greatly varied throughout the test versions. This suggests that experience with former items influences performance.

All participants were asked to self assess their computer skills and computer usage per week. There are significant gender differences in both. This could mean that male participants have higher computer skills than female testees. In addition men use computers more hours per week than women amongst our participants.

It is interesting that self assessment regarding correctly solved items in the DSTAR test correlates high with the person's real result (0,756).

In order to improve usability and technical aspects of the DSTAR environment users were asked to rate the menu interface and usability in general (including informal comments). On a scale from 1 (min) to 5 (max) users rated the comprehensibility and usability of the menu interface with 4,65 (σ = 0,72) which is very high. There are no significant gender differences (male 4,53; female 4,72). This indicates that interaction design as described in 3.2 is functional.

Users reported other usability problems that can be summarized in two categories: wireless pen problems (mostly) and HMD problems. Since we limit test duration to a maximum of 30 minutes hardly any participants report side effects of using HMDs known as simulator- or cyber-sickness [14]. More often wireless communication of the pen interaction device failed and no button clicks were transmitted. This can be frustrating and interrupts concentration on the task. A solution is a new wireless pen that is currently being tested. For reliable communication a cabled version is also being considered.

5. CONCLUSION AND FUTURE WORK

Virtual reality applications promise an ecologically valid way to assess spatial abilities and offer - in addition to traditional tests - new possibilities to gather important data. The spatial test we are developing tries to make optimal use of these possibilities. We do not only measure how much the testee has already been trained but also how much he or she could profit from practice with spatial tasks. This may be of great importance for example in the selection of participants for technical schools or courses. Through its possibilities for hands-on interaction with the stimulus material, virtual reality offers particularly interesting possibilities for the training module of a dynamic test. Hands-on practice has been shown to be one of the most effective ways of improving spatial ability. Thus our technology has advantages for measuring and training spatial skills both compared to other computer technologies and compared to the manipulation of real objects, which has clear physical limitations (e.g., when it comes to intersecting or transforming objects).

We plan to extend DSTAR to a short-time dynamic test consisting of pretest, training and posttest taking place within one or two sessions. The pretest shall be also applicable as a stand-alone assessment tool.

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