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ABSTRACT: Mental rotation ability is seen as an important condition for the development of professional competence in many technical professions. Previous studies have shown that mental rotation can be trained by repeatedly performing mental or manual rotations. Virtual technology opens up the possibility of capturing and training mental rotation ability in near-reality environments. So far, there is little empirical evidence on the potential and effectiveness of virtual environments to analyse and enhance this ability. This study is intended to generate findings on the VR-based, adaptive training of mental rotation ability for the development of a support measure. A pre-post examination of mental rotation ability was chosen as the design of the study. Two virtual phases took place between the pre- and post-inquiry, in which the test persons (mainly students, N = 100) dealt with virtual 3D items. It was shown that the mental rotation ability of the test subjects improved after working with virtual items. Furthermore, the results provide information on the suitability of the virtual 3D items for measuring and the adaptive training of mental rotation. The flaws of the study and the prospects for designing an adaptive, VR-based form of mental rotation training are discussed.

Keywords: Virtual reality, mental rotation ability, mental rotation training

Training der mentalen Rotationsfähigkeit in virtuellen Räumen

ZUSAMMENFASSUNG: Die mentale Rotationsfähigkeit wird als eine wichtige Voraussetzung für die Entwicklung der Fachkompetenz in vielen technischen Berufen angesehen. Bisherigen Studien zufolge kann die mentale Rotationsfähigkeit durch wiederholte Ausführung mentaler oder manueller Rotationen trainiert werden. Virtuelle Technologie eröffnet die Möglichkeit, die mentale Rotationsfähigkeit in realitätsnahen Umgebungen zu erfassen und zu trainieren. Bislang liegen wenige aussagekräftige empirische Erkenntnisse zu den Einsatzmöglichkeiten und der Effektivität von virtuellen Umgebungen zur Analyse und Förderung dieser Fähigkeit vor. Mit dieser Studie sollen anschlussfähige Befunde über die VR-basierten, adaptiven Trainings der mentalen Rotationsfähigkeit zur Entwicklung einer Fördermaßnahme generiert werden. Als Design der Studie wurde eine Prä-Post-Untersuchung der mentalen Rotationsfähigkeit gewählt. Zwischen der Vor- und Nacherhebung fanden zwei virtuelle Phasen statt, in welchen die Probanden (überwiegend Studierende, N = 100) virtuelle 3D Items bearbeiteten. Es zeigte sich, dass sich die mentale Rotationsfähigkeit der Testpersonen nach der Arbeit mit virtuellen Items verbesserte. Darüber hinaus geben die Ergebnisse Aufschluss über die Eignung der virtuellen 3D Items zur Erfassung und zum adaptiven Training mentaler Rotationsfähigkeit. Die Schwächen der Studie sowie die Aussichten zur Gestaltung eines adaptiven, VR-basierten mentalen Rotationstrainings werden diskutiert.

Schlüsselwörter: virtuelle Realität, mentale Rotationsfähigkeit, Training der mentalen Rotation

1 Introduction

Virtual reality (VR) is a computer-generated three-dimensional (3D) representation of real or fictitious environments in which the user can enter and perform near-realistic actions. According to embodied cognition theory, physical conditions and actions have a basal influence on human cognition (Wilson 2002). Following this approach, complex interactions with the environment, whether real or virtual, play a decisive role in learning. The so-called fully immersive (FI) virtual environments are characterised by the fact that they allow the use of natural user interfaces (e.g. head-mounted display, Leap Motion, data gloves, etc.), thus enabling the user to interact with virtual objects, perform actions, and move in virtual space in a natural way (Ariali & Zinn 2020; Mohler 2000). A special feature of immersive virtual environments is the possibility to perceive the environment egocentrically. The egocentric perception of objects and relationships is responsible for success in different domains and shows different relationships than in real-world performance (Kozhevnikov et al. 2013). In view of these advantages, VR provides the opportunity to implement training sessions that require a realistic interaction with the environment and would be too complicated or too expensive under real conditions. Especially for those areas that require spatial imagination, VR can be effectively used to train certain abilities and to study different aspects of spatial behaviour and spatial skills (Dünser et al. 2006). Mental rotation ability (MRA) is one such area that has often been studied in the context of virtual environments (Ganis & Kievit 2015; Kozhevnikov & Dhond 2012). This ability, as an important part of spatial imagination and therefore of human intelligence, is a necessary condition in many scientific and technical professions. Due to its importance, the possibilities of promoting mental rotation ability received a lot of attention for a long time. Meanwhile there is enough empirical evidence that MRA can be trained. Although the trainability of mental rotational ability is generally well proven, there are hardly any empirically validated instruments for the targeted support of this ability in adulthood. Attempts to train MRA by using VR-based technology have also often failed. The reasons for this could be the limited possibilities of using non-immersive technologies in particular. Unlike non-immersive or partially immersive (PI) technology, FI technology allows to immerse oneself almost completely in a virtual world. For example, the combination of the VR system HTC-Vive with Leap Motion technology offers users, in addition to 3D representation, the possibility of interacting with virtual figures in a realistic way. HTC-Vive uses an optical tracking system in which two base stations are placed at opposite sides of the room (Hagen 2017). With the help of integrated infrared LEDs and two lasers, one each for the vertical and horizontal axes, the base stations cover an area of 5 x 5 metres in which the user can move. For interaction with the virtual objects, Leap Motion technology can be integrated into the application in addition to the conventional controllers. This recognises the user's hands and allows gesture-based control.

In addition to the realistic design possibilities of the training, virtual environments allow the integration of motivational elements and processes. These can be realised, for example, in the form of animations, gamification or the user-oriented, adaptive design of learning materials. In e-learning research, adaptive learning environments are given significant meaning, as they can personalise the learning content and the learning process (Rey 2009). These are designed in such a way that they adapt learning materials according to the learner's needs or skill level, as indicated by their responses to tasks. By specifying learning-relevant materials, acceptance and learning efficiency can be increased in addition to learning motivation (Thalmann 2014).

The possibility of training mental rotation skills in a FI virtual environment with adaptively designed learning materials opens up new perspectives for the development and investigation of new support concepts. This study is intended to generate findings for the VR-based evaluation and future adaptive support of the MRA to develop a training program. For this purpose, virtual 3D figures are constructed in which the number of cuboids is varied as difficulty-determining features assumed *a priori*. The test persons had the possibility to interact with the virtual figures in two different phases in a realistic way. The first phase served as a test phase and the second phase as a training phase of MRA. Before and after the virtual phases, the paper-and-pencil based MRA of the persons was determined. If dealing with the virtual tasks had a positive training effect, MRA (measured by a paper-and-pencil test according to Peters et al. (1995)) should have improved after the virtual phases. For the future adaptive design of a training session, it would also be important to know whether the difficulty-determining features assumed *a priori* actually influence the task difficulty for the persons. The task difficulty can be determined by the Item Response Theory (IRT; Rasch 1960) scaling of solution data. Based on these considerations, the following questions were to be answered by the analysis:

- How does the virtual phases affect the mental rotation ability?
- How do difficulty-determining feature assumed *a priori* (the number of cuboids of an item) correlate with IRT-based difficulty determination of the tasks?

Furthermore, to design innovative and efficient training environments, paper-and-pencil tests need to be replaced by the digital alternatives. This would require the development and validation of such tests. In the context of this study, this issue was considered, and after IRT scaling of the virtual mental rotation test (MRT) items from the first virtual phase and thereby determination of the personal abilities, the following question was formulated:

- How is the MRA measured by paper-and-pencil MRT related to the MRA measured by virtual MRT?

In this regard, the second section of this article deals with the theoretical and empirical foundations and the training of MRA. The third section defines the research questions. In the fourth section, the methodological approach of the study is explained, followed by a report on the results in the fifth section. In the sixth section, the central findings are discussed before finally summarising the study.

2 Theoretical and empirical background

2.1 VR-Technology

The dynamic dissemination of new technologies is associated with fundamental processes of change and reveals a great potential to optimise educational opportunities. With the integration of digital technologies, innovative learning and working environments can be created to make teaching and learning processes more flexible, individualised, analysed, and optimised. One of these possibilities is virtual reality (VR), which allows learning in realistic simulations and thus offers numerous advantages: VR makes it possible to simulate fictitious environments that would be impossible or too dangerous in real conditions (Schuster 2015). Furthermore, it is possible to modify parameters that often cannot be changed in a real system, e.g. change of gravity (Potkonjak et al. 2016). The modifications and changes can be reversed just as easily. The use of VR allows researchers to create the exact same conditions for all participants or to vary certain environmental variables in real time, giving researchers more control over experimental settings (Dünser et al.

2006). An additional advantage of using computer-generated environments is the possibility to automatically log data relevant to the study, providing an efficient alternative to other data collection methods (Dünser et al. 2006). The data can not only be collected in real time, but also automatically analysed and reported back to the persons directly. The system can also take the collected data into account and incorporate it into the adaptation of the learning environment of the learner.

Due to numerous advantages, virtual realities have long been researched (Cipresso et al. 2018). There are also numerous differentiations of virtual environments (Fuchs 2017). According to the most common understanding, VRs are computer-generated real-time representations of real or fictitious environments, which enable a special kind of human-machine interaction by enriching them with artificial or increasingly natural user interfaces. The specialty of VR is the experience of being in a foreign place (Rheingold 1992). The situation in which the virtual environment is perceived as real is called immersion, and corresponding virtual environments are described as immersive. Typically, immersive environments are divided into fully immersive (FI) and partially immersive (PI) virtual environments (Ariali & Zinn 2020). Due to technological limitations, the feeling of immersion can only be conveyed to a limited extent in today's VR environments. Nevertheless, the technology which can give the highest feeling of immersion is often called FI (Ariali & Zinn 2020). FI environments are characterised by the use of natural user interfaces (including head-mounted display, gesture control). This allows the user to interact with virtual 3D objects in a natural way, perform actions, and move around in virtual space. Since the user's position in space is constantly recorded, it is possible to move around in the virtual environment in an egocentric perspective and to explore it visually and aurally (Korgel 2017). The disadvantages of the FI environment are the higher technological effort and the limited mobility of the necessary equipment. On the other hand, PI solutions are characterised especially by the high mobility of their equipment. Similar to FI environments, PI environments allow an egocentric representation of space and objects; natural user interfaces are also available, but the possibilities for interaction are limited. For example, the user cannot walk around virtual objects naturally and view them from different perspectives. A technological example for the realisation of a PI environment is the pair of VR -glasses Samsung Gear, which allow a stereoscopic, egocentric VR representation but only provide limited movement and interaction possibilities.

PI technology is often used to implement virtual learning environments due to the generally favourable availability and good mobility of the equipment. However, it can be assumed that, in addition to the egocentric representation of the environment, the possibility of changing perspectives through natural walking can be beneficial for learning, which is currently only supported by FI environments. The study by Ariali and Zinn (2020) showed that 3D mental rotation tasks can be solved more quickly in FI virtual environments than in PI environments. Therefore, a FI virtual environment is recommended for the realisation of pedagogically valuable learning and training environments which involve spatial relationships (Ariali & Zinn 2020).

The current state of research also proves the advantage of immersive technologies over a computer desktop in some areas. These are mainly applications which involve spatial arrangements and contexts. In contrast to desktop-based representation (a non-immersive environment), the user has a view from an egocentric perspective in immersive virtual environments, which corresponds to a realistic perception of the environment and its objects (Dede 2009). Additionally, the possibility of movement allows the perception of space and objects from different angles and can thus help to facilitate the processing of spatial information. Already 20 years ago, Pausch, Proffitt and Williams (1997) concluded that training with desktop PCs was of limited efficiency for the development of reality-related skills and subsequently used precursors of immersive technology in visual-spatial search tasks. The results of Pausch, Proffitt and Williams (1997) indicated that the new VR technology can be used to solve such tasks more efficiently. Murcia-López and Steed (2016) also showed that complex spatial knowledge tasks are solved in virtual environments at a higher rate than in desktop-based environments. Dan and Reiner (2017) explained this by the fact that the use of immersive virtual environments leads to a lower cognitive load and more efficient processing of visual stimuli for users compared to two-dimensional content. Furthermore, other studies have indicated that people with a lack of spatial imagination especially benefited from immersive virtual environments (Dan & Reiner 2017; Ariali & Zinn 2018). The overloading of the brain by a series of cognitive operations can be used to explain this connection. Such cognitive operations are mental rotation and visual spatial transformation, which are necessary in screen-based activities to carry out a change of perspective (Zacks & Michelon 2005). Virtual perception is strictly egocentric and seems to be based on an implicit, automatic coding mechanism (Nico & Daprati 2009) which may facilitate information processing. The possibility of a VR-supported egocentric perception of 3D objects can thus be helpful in constructing adequate 3D mental images of the learning content.

2.2 Mental rotation ability

The mental rotation ability describes the ability to rotate 2D or 3D figures and objects mentally, i.e. in thought (Linn & Petersen 1985). It can be classified under the spatial imagination, which again is an important facet of human intelligence (Hegarty & Waller 2005). The construct of spatial ability can be further divided into several subfactors. Linn and Peterson (1985) distinguished three categories of spatial abilities based on different processes relevant for solving different types of tasks. The three categories are (1) spatial perception, i.e. the perception of spatial relations between objects and in relation to the localisation of one's own body, (2) spatial visualisation as processing and manipulation of spatial information in several steps, and (3) mental rotation.

Mental rotation describes mental simulation of an object's rotation in space (Hegarty & Waller 2005) and requires cognitive processes to imagine how objects will appear when they are rotated (Jäncke & Jordan 2007; Heil & Rolke 2002). According to some views, these cognitive processes are associated with physical rotation and cause the activation of motor representations associated with the actual physical rotation of objects (Adams et al. 2014; Steiff et al. 2018). To support this view, Wohlschläger and Wohlschläger (1998) proposed the hypothesis of the "common process", which states that there is a common process that controls both the motor commands for manual object rotation and the change in cognitive processes for mental rotation. Wohlschläger and Wohlschläger (1998) proved their theory in a series of experiments in which mental and simulated manual rotation were compared for the same stimuli. In rotations around Cartesian axes, they found that the reaction times of manual and mental rotation were functionally connected. The assumption of Wohlschläger and Wohlschläger (1998) is also supported by the results of Shepard & Metzler (1971) who demonstrated a linear relationship between the angle of rotation of the figure and the speed of mental rotation. Hence, angular disparity has been considered an important difficulty-determining characteristic of rotational figures. According to Steiff et al. (2018), the complexity of the stimulus can also have an impact on mental rotation. The authors used the tasks from the subject of chemistry, which requires mental rotation to compare the molecules. They observed that the performance of the participants decreased as the spatial complexity of the molecules increased. For stimuli which contained molecular representations with two asymmetric axes, participant accuracy was reduced, and response time increased compared to stimuli with a single asymmetric axis (Steiff et al. 2018). Since the stimulus complexity can be expressed in further facets besides the number of axes, more detailed research is needed to show which factors interfere with mental rotation and to derive support requirements.

Mental rotation has so far been studied in various contexts and is considered an indispensable skill in many academic fields (including mechanical engineering, architecture, anatomy, medicine, biology, geology, etc.) as well as in several commercial and technical professions (Eliot 2017; Castro-Alonso & Uttal 2019). Especially in the digitalised and competitive working environment of the 21st century, it is becoming increasingly important to be able to understand, use, and think about different forms of information (Lane, Lynch & MCGarr 2019). MRA is indispensable to be successful in technical professions (Halpern 2000). The importance of this ability for scientific and technical disciplines has also been empirically proven several times. Sorby and Baartmans (2000), Sorby et al. (2013), and Veurink and Sorby (2019) showed that an improvement in spatial skills, and especially mental rotation ability, can lead to better performance in the areas of maths, computer science, natural science, and technology (MINT). There are significantly high positive correlations between mathematical skills and spatial abilities (Mix et al. 2016; Sella et al. 2016). Goktepe and Ozdemir (2020), for example, were able to show in their quasi-experimental study that engineering and design-oriented mathematical activities have a positive effect on the development of students' spatial abilities. This confirmed the results of previous studies in which similar approaches were used (Sorby & Baartmans 1996; Hegarty & Waller 2005).

MRA is often measured with the mental rotation test (MRT), which was originally established by Shepard and Metzler (1971) and further developed by Vandenberg and Kuse (1978). The test tasks of Shepard and Metzler (1971) involved the comparison of two simultaneously presented stimuli, whereby the right stimulus represented a version of the left stimulus rotated and/or mirrored by different angular disparities.

Revised versions of the MRT are currently available (Vandenberg & Kuse 1978; Peters et al. 1995). In the MRT version by Peters et al. (1995), test subjects were shown one initial figure and four comparison figures. Two figures were rotations of the target figure, the other two figures were not identical to the target figure and usually showed a mirrored figure. The task of the test person was to mark exactly the two comparison figures that corresponded to the original figure. In total, the test consisted of 24 of such items (sometimes also 12 items with two different sets), which had to be completed under time pressure (Hausmann 2007).

In the past, due to the importance of MRA described above, MRT has attracted great attention in spatial-visual and general intelligence research. Fortunately, there is considerable evidence showing that mental rotation can be trained (Uttal et al. 2013). Based on the "common process" hypothesis (Wohlschläger and Wohlschläger 1998), research on mental simulation training assumes that manual training can improve MRA. There is much empirical evidence for the effectiveness of manual training for mental rotation (Adams et al. 2014). New technologies, such as 3D computer simulations or immersive VRs, enable the implementation of manual training environments. A special feature of training with manual rotations is that immediate visual feedback is always available during the manual rotation (Adams et al. 2014), which is an important factor for the effectiveness of the training (Dihoff et al. 2003). In addition, virtual environments allow the integration of further feedback actions such as sound, change of color, size, etc. Furthermore, the technology offers extended possibilities to obtain more precise and comprehensive information about cognitive processes when solving MRT tasks. For example, Parsons et al. (2004) developed a new measurement method of virtual reality spatial rotation (VRSR) based on the stimuli from MRTs. The authors found that the cognitive processes that occur during the solving of VR-based mental rotation tasks are comparable to the cognitive processes that are activated during the solving of paper-and-pencil MRT tasks. In a later study by Kozhevnikov and Dhond (2012), the mental rotation ability in a traditional 2D non-immersive, 3D non-immersive, and 3D immersive environment was investigated and compared. The results showed that rotations around the Z-axis were processed more slowly in the immersive condition than in the non-immersive condition. According to the authors, this could be due to the additional egocentric information that could be provided in the immersive environments, which leads to a deeper processing of the stimuli. Under this assumption, the use of VR for training mental rotation could prove to be particularly advantageous.

3 Research questions

The assessment and support of MRA in VR environments is a poorly explored and implemented area despite a long research tradition and contains much undiscovered potential. An egocentric view of the rotating figures on the one hand and the possibility of interaction, e.g. manual rotations of the figures, on the other hand could lead to a significant improvement of MRA, which should also be measurable by the paper-and-pencil MRT. VR-based mental rotation tasks were created based on the self-developed 3D items to realise the virtual experience. The participants could solve the tasks in a FI environment by interacting with the 3D objects in a realistic way and make decisions regarding the equality of the figures. The expectation was that after dealing with virtual figures, an increase in MRA could be measured in a paper-and-pencil test (Peters et al. 1995). Therefore, the first research question was as follows:

- How does the virtual phase affect the mental rotation ability?

In the future, further potentials of virtual environments can be improved to become more efficient for training mental rotation ability. One such possibility would be the adaptive design of training tasks. In such an approach, the system would determine the difficulty of the given task depending on the person's solution behaviour and thereby avoid overwhelming or underchallenging the person. An important issue in this context would be the criteria used to manipulate the difficulty of the tasks. In the literature, the angular disparity of the figure is known as a difficulty-determining feature of MRT tasks (Shepard & Metzler 1971). There is also evidence that the complexity of the figures may also correlate with the difficulty of the task (Steiff et al. 2018). However, there is a lack of empirical evidence for this assertion in the MRT context, which is one of the issues addressed in this study. It was investigated in the VR context to what extent the complexity of the virtual MRT figures influences the difficulty of the tasks determined by the IRT analysis. An IRT analysis allows to calculate latent task parameters based on the solution behaviour and to place them together with the personal abilities on a logit scale. Due to its numerous advantages over classical test theory, IRT is a widely used method (Bortolotti et al. 2013) to evaluate performance data and to determine the task difficulties in adaptive test designs. This study also investigated whether the determination of difficulty by the complexity manipulation of the figures can also be confirmed by the IRT scaling of the solution data. It was formulated as a second research question:

- How does the difficulty-determining feature assumed *a priori* (the number of cuboids of an item) correlate with IRT-based difficulty determination of the tasks?

In addition, this study addressed the question to what extent the MRA can be captured directly in the VR environment. This finding is relevant for further studies since the VR environment could replace the paper-and-pencil tests. Digitally measured and stored data could be automatically evaluated and, if necessary, directly reported back to the individuals. In this regard, the following question was formulated:

- How is the MRA measured by paper-and-pencil MRT related to the MRA measured by virtual MRT?

4 Method

4.1 Participants

100 participants were recruited voluntarily. Forty-seven (47 %) were female and fifty-three (53 %) were male. Mean age of the participants in the study was 25.11 years with a standard deviation of 6.73 years (minimum 16 years, maximum 50 years). All of them were right-handed and none had ever participated in any MRT task before.

4.2 Design

The study consisted of a pre-test post-test design. It used the paper-and-pencil-based MRT for both tests. The results of the pre-test reflect the value of the original expression of the mental rotation and were compared as a reference value with the result of the post-test. Two virtual units (phases) took place between the pre-test and the post-test. The first phase was the test unit, in which the participants had to decide which two of the four figures corresponded to the given figure, but they did not receive any feedback on their response from the system. The second VR unit allowed the figures to rotate into the correct position. If the task was solved correctly, the system gave additional feedback, so a training effect could be assumed. In addition to testing the effectiveness of the VR-based mental rotation training, the study also aimed to determine the suitability of the tasks for adaptive training. To this end, the difficulties for the virtual MRT items were determined by an IRT analysis. Furthermore, it examined whether the number of cuboids of the 3D figures could be identified as a difficulty-determining feature. Finally, the correlation between these two test variables was reported to investigate the substitutability of paper-and-pencil MRT with virtual MRT.

4.3 Materials

The materials used in the study were the MRT (Peters et al. 1995), the VRSR system, and the technology required to create the VR environment. These are described in detail in the following subsection.

4.3.1 Technology

The following technologies were used to implement the VRSR system: a head-mounted display (HMD) connected to a computer (with a 64-bit Windows 10 operating system, with an Intel(R) Core(TM) i7 2.67 GHz processor, 8 GB RAM and a NVIDIA GeForce GTX1070 graphics card), and the Leap Motion technology. The HMD used was the HTC Vive Pro developed by HTC and Valve Corporation; the HTC headset contained two lighthouse base stations capable of tracking the HMD within a specific 5 by 5 m area by a calibration process. The Leap Motion technology is a small USB device that uses optical sensors and infrared light to track hands: it was attached to the HTC Vive with a special bracket in the front and centre part of the HMD. It is possible to easily display hands in VR and to interact with virtual objects in a realistic way with this special configuration.

4.3.2 MRT

The paper-and-pencil-based MRT was used in the form modified by Peters et al. (1995) to measure mental rotation ability. The MRT of Peters et al. (1995) comprised 24 multiple-choice tasks that included 2D drawings of 3D figures. Each task contained a target figure on the far left of the page and four alternative answers on the right. The answer alternatives included two identical drawings as the target figure, shown from a different perspective, and two distractors. The test subjects' task was to mark the two comparison figures that matched the source figure.

The 24 items were divided into two halves (version A and B) and were given in paper-and-pencil form before and after the virtual phases to allow a pre- and post-test assessment of MRA and to avoid test repetition effects. The subjects who were given test version A as pre-test were given version B as post-test and vice versa. In total, half of the persons (n = 50) received variant A and half (n = 50) were given variant B as pre-tests. A maximum of 12 points could be achieved in each test version. In case of a positive training effect, the test persons should, on average, achieve better results in the post-test than in the pre-test.

4.3.3 VRSR system

Tab. 1 shows the two phases of the VRSR system with their properties. Both phases consisted of 30 items each and were based on immersive VR and Leap Motion technology. While the figures could be selected by hand in the first phase, they could be rotated and brought into the appropriate position in the second phase. The given processing time for a task was 30 seconds in the first phase and 40 seconds in the second phase, because the more complex form of interaction took more time. After the specified time had expired, the system automatically switched to the next task. If the task was not solved in the specified time interval, the system saved the task as not solved.

Tab. 1: Description of phases 1 and 2 from the VRSR

	Virtual phase 1	Virtual phase 2
Number of items	30	30
Technology	HTC VIVE + Leap Motion	HTC VIVE + Leap Motion
Form of interaction	Selection of the figures by using the hand grip	Manual rotation of the figures
Feedback	The selected figures change colour	The figures only change colour if correctly rotated
Processing time	30 sec per item	40 sec per item
Log data	solved / not solved	solved / not solved

The virtual mental rotation tasks in the two phases were developed based on the MRT items by Shepard and Metzler (1971) but were modified to increase the difficulty by varying the number of cuboids from three to six. Figure 1, for example, shows the figures with four, six and three cuboids. In terms of their structure, the virtual MRTs were similar to the classic MRT tasks.

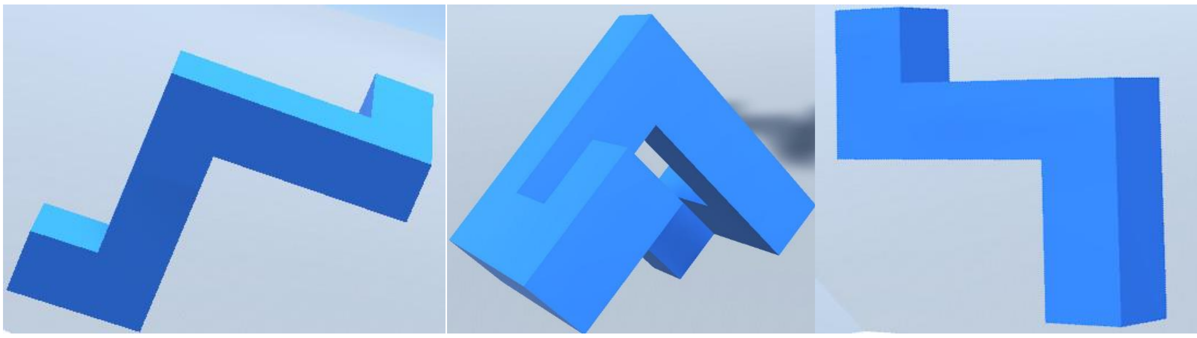

Fig. 1: Examples of the figures contained in the virtual MRT, which were constructed with software Blender according to the 3D figures of Shepard and Metzler (1971). The complexity of the figures was varied depending on the contained cuboids. The figures shown here contain four, six and three cuboids.

There was also a target figure in virtual space, which was presented as green in front of a board (Fig. 2). The four blue-coloured figures represent the possible answers, which included two correct or identical figures to the target figure. In the first phase, the blue figures could be coloured green by using a handle which corresponded to the selection of correct figures. In the second phase, the blue figures could be rotated on their X, Y, and Z axes. As soon as a blue figure was placed in the same position as the green figure, it changed colour and turned green as well. The Leap Motion technology allowed the interaction (grasp or turn) to be performed by the participant's own hands. The software *Blender* and the game engine *Unity* were used to program and develop the test sequences.

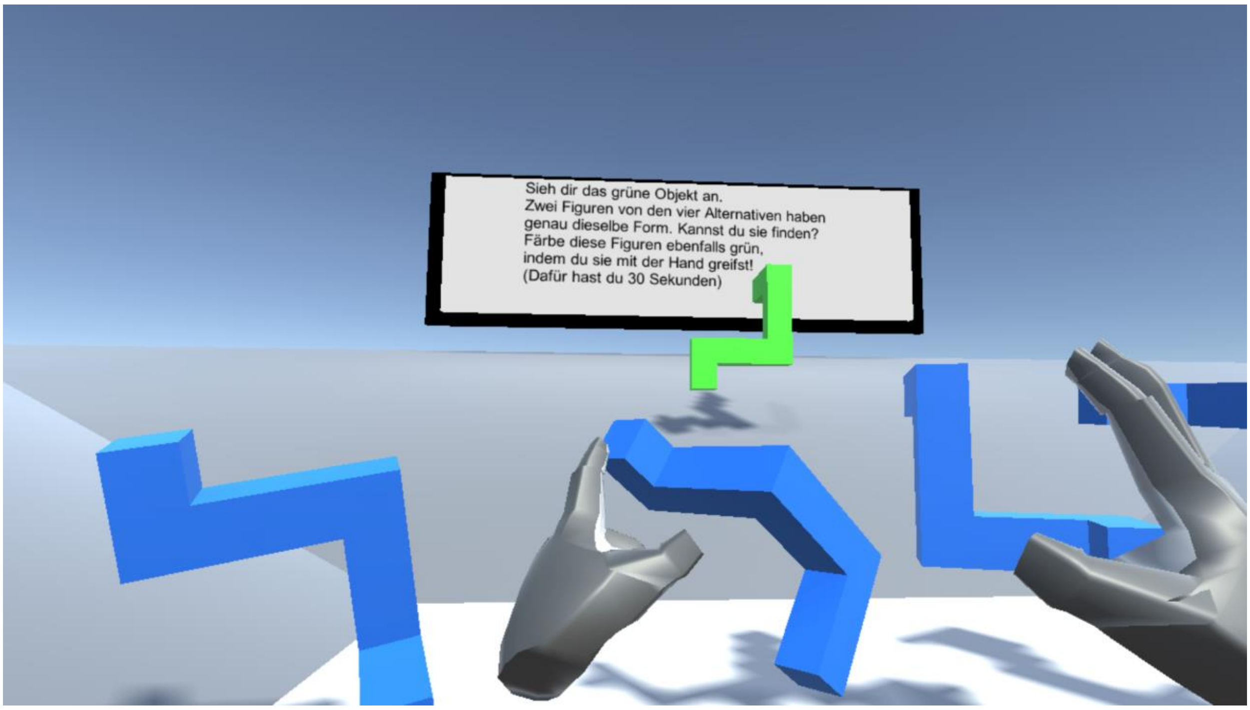

Fig. 2: A scene from the virtual MRT: According to the instructions on the task board, the test persons had to select two of four blue figures corresponding to the target figure (green figure in front).

4.3.4 Procedure

An individual examination, which was carried out in a room specially prepared for the study by an experimenter, lasted about 60 minutes and consisted of four sequences (Fig. 3).

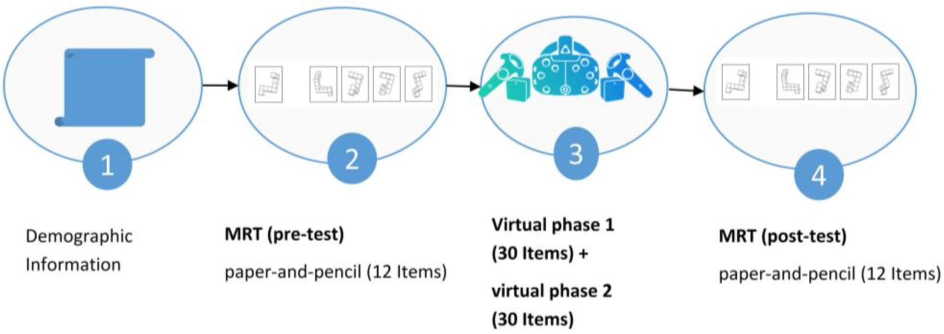

Fig. 3: Schematic illustration of the study procedure consisting of four different sequences: Demographic questionnaire, pre-test of paper-and-pencil MRT (half of the tasks from MRT according to Peters et al. 1995), virtual phases and post-test of paper-and-pencil MRT (other half of the tasks from MRT according to Peters et al. 1995).

After a greeting, a short introduction to the project, and an explanation of what the participant could expect in the next hour, the first questionnaire was handed out (sequence 1). This questionnaire was used to record the demographic information of each person. The data included, inter alia, the sex, the age, and the current educational level of the subject.

After the questionnaire was filled out, the first part of the MRT with 12 items followed (sequence 2). Each participant was given five minutes to solve the tasks in the test. A short introduction to the task was given prior to the test. The pre-test was followed by the first virtual phase (sequence 3). An example of virtual MRT task was shown to the participants by an image printed on paper. This gave them an overview of what they were going see in VR and what the task was going to be. The analogy to the standardised test on paper was explained. For example, the green object represented the target object, and the blue figures represented the four possible answers, of which two were identical to the target object. Thus, the participant was able to see the similarities between the paper-based test and the virtual test. Subsequently, the test person was shown the technology and the acuity regulation of the HMD, with which the visual acuity in the VR space could be individually adjusted. The participant put on the HMD while the test supervisor made sure that the HMD were firmly placed to the head. The person was turned in the correct direction so the objects and features in the exercise sequence could be seen in virtual space. In the exercise sequence, a blue figure was seen first, as well as the board on the wall on which the task was written. The participants first had to get used to the virtual world and find their way around. During this exercise, the experimenter gave instructions and hints to move the figure around and to look at it from all sides. Afterwards, the first use of the hand models simulated in virtual space followed. The simulated hand movements corresponded to the real hand movements of the participant which were tracked by the Leap Motion sensor on the HMD. In the first exercise of the first virtual phase, the test person was instructed to reach for the figure. With this particular hand movement, the blue figure was coloured green. Further exercises followed, which corresponded to the task style of the subsequent test in virtual space. A green target object and the four different blue possible answers could be seen in front of the board. Two identical figures had to be coloured by grasping them with the hand. The participant was able to mark all four blue figures in green but could not undo this. The test person therefore had to think carefully before deciding which figures should be coloured. Afterwards, the actual testing began. Each participant had to solve 30 tasks in the test, each within 30 seconds’ processing time. A short break was taken at the end of the first phase before the second phase in virtual space followed. During this short break, the test person could briefly lift HMD to relax in the real environment.

The second phase followed shortly thereafter. This phase was the virtual training, as the test person now received feedback when he or she either solved the task correctly or incorrectly. The tasks and figures were identical to the tasks from the first testing phase. The difference now was that the test person had the possibility not just to reach for the figures to mark them, but also to rotate the figures. Again, there was a practice sequence before the actual training started. In the first exercise, the participant had to rotate the single blue figure seen into exactly the same position as the green target object in the background. This type of task was repeated a few times, so that the test person could get used to handling and rotating the virtual objects. This was followed by further exercises, but in the style of the subsequent training exercises. This meant the participant again had to choose two identical figures from the four alternatives and place them in the correct position, such as the green target figure. As soon as the figures were in the correct position, they turned green. The test person received feedback here, as only those figures which were identical to the target figure turn green.

After the exercise sequence, the test person was instructed to complete 30 tasks. Also, the test person did not have unlimited time for this, but exactly 40 seconds for each task. After the second phase, the virtual testing and the training in virtual space was over. The second questionnaire subsequently followed which asked participants about their personal opinions on the virtual tasks and the individual degree of difficulty was measured. Immediately afterwards, the second part of the

MRT (sequence 4) was presented to the test person. As before, the person had five minutes for this test. The overall experiment ended with the last test.

5 Results

The analysis was performed with the program R (version 3.4.4) using the package "TAM" for the IRT analysis (Robitzsch, Kiefer & Wu 2019). The MRT data as well as the sum scores of the virtual MRT were normally distributed, which allowed the use of parametric t-tests for group comparison.

Table 2 shows the descriptive results (mean value, standard deviation) for all examined constructs MRT (pre-test), MRT (post-test), virtual MRT (phase 1) and virtual MRT (phase 2) to provide a first overview of the distribution of the different test scores.

Tab. 2: Descriptive results

	Maximum possible score	Mean (M)	Standard Deviation (SD)
MRT (pre-test)	12	7.36	3.1
MRT (post-test)	12	7.92	2.92
virtual MRT (phase 1)	30	13.72	5.43
virtual MRT (phase 2)	30	17.08	5.92

The impact of the virtual phase on MRA was examined to the first question of the study. It was expected the paper-and-pencil test based MRA to be higher after the virtual phase than before. This was verified using a t-test for dependent samples. The results show that the mental rotational ability after the virtual phase was significantly better than it was before the virtual phase ($t(98) = 2.222$, $p < .05$, $d = 0.224$).

It was determined whether the virtual MRT items were IRT scalable to answer the second question. The analysis was performed according to the criteria of the one-parameter, one-dimensional Rasch model (1PL model, Rasch 1960). By the analysis method, the personal abilities and the item difficulties are displayed on a common logit scale, whereby in this case, the mean value of the item difficulties marked the zero point. The personal abilities were described by a histogram, while the item parameters were arranged along the Y-axis according to their difficulty level. The test quality was assessed by WLE and EAP/PV reliabilities as well as by the weighted mean square values within the limits of $0.77 < wMNSQ < 1.33$ (Bond & Fox 2013). The results show a good fit between the model and the collected data. The EAP/PV reliability was .801 and WLE reliability .845. The weighted mean squares were between .79 and 1.19. The connection between personal skills and task difficulties was illustrated by a Wright map in Figure 4. The personal abilities and task difficulties were symmetrically distributed around the zero point and range from -3 (very easy items) to 3 (very difficult items). The Wright map also shows that the items were largely heterogeneous in terms of difficulty and covered almost the entire personal ability range, so that suitable tasks can be found from the task tool for each ability level, which is necessary for the development of adaptive training materials.

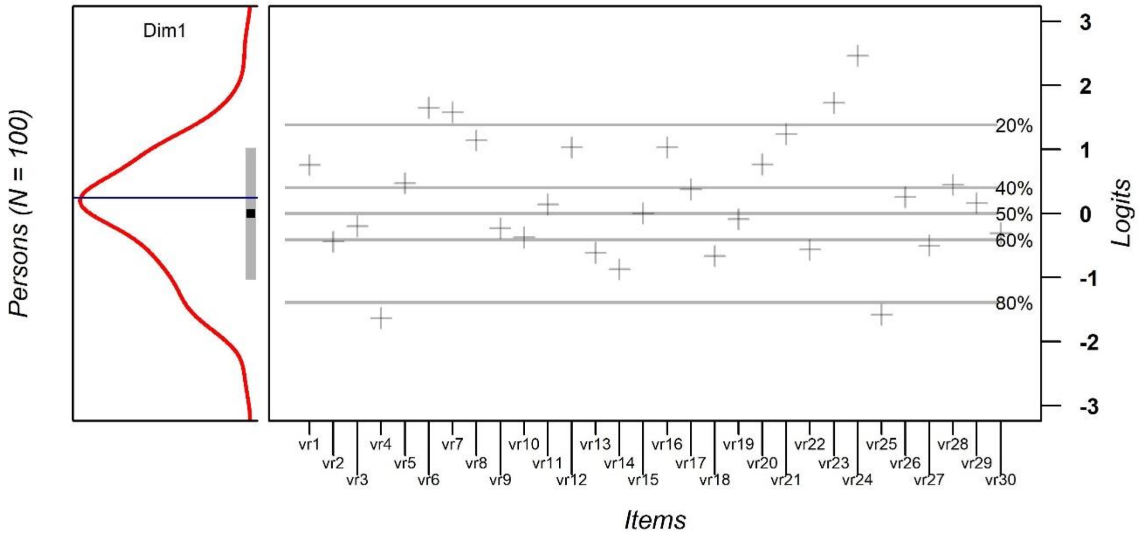

Fig. 4: Wright map: personal abilities (WLEs) are shown on the left side of the Wright map by a histogram, while the item parameters are arranged on the right side and are represented by grey crosses.

The next step to answer the second question was to investigate the relationship between item difficulty (determined by IRT analysis) and the number of cuboids in virtual MRT figures. It was expected that the number of cuboids to correlate positively with the difficulty of the task. The correlation analysis showed a significant positive correlation between the number of cuboids and the difficulty of the task ($r = .417$, $p < .05$).

Finally, it was examined whether and to what extend the paper-and-pencil test based MRA is related with the virtual MRA. To determine the virtual MRA, personal abilities (WLEs) calculated by IRT scaling the data from the first virtual phase were considered. By the analysis of correlation, a high positive correlation between MRT (pre-test and post-test) and virtual MRT (phase 1) ($r = .620$, $p < .001$) was discovered.

The results of the study confirmed the expectations. It was shown that MRA improves after the virtual phase, that the difficulty of virtual MRT items is related to the complexity of the figures (number of cuboids), and that the paper-and-pencil test based MRA is highly correlated with the MRA measured by virtual MRT.

6 Discussion

This study investigated whether and how VR can support MRA and generated findings on the VR-based, adaptive training of mental rotation ability. To this end, three main research questions were answered:

First, it had to be clarified whether virtual training improves the mental rotation ability of test persons. The results showed a significant improvement of this ability after the virtual phase, which indicates the effectiveness of VR training. However, the methodological weaknesses of the study should be pointed out here: the study design consisted of a pre-test and post-test design but lacked a control condition that could verify that the effect shown was not present without training. Simply dealing with the pre-test tasks of MRT might have led to the improvement of MRA and to better results in the post-test. This should be considered in future studies to assess the effectiveness of training.

The second objective of this study was to identify a difficulty-determining feature of virtual MRT figures. The aim was to optimise the virtual training program by making it adaptive, i.e. adapting the task difficulties to the personal abilities. Previous studies (Shepard & Metzler 1971) were able to identify the angle of rotation of the figures to the target figure as a difficulty-determining feature. It was suspected that the difficulty of the task would be additionally influenced by the complexity of the figures. It should be more difficult to mentally rotate a figure with more edges than a figure with few edges. To this end, the number of cuboids in this study varied between three and six, and then an IRT analysis was carried out to determine the difficulty of the task.

The IRT analysis made it possible to sort the test items by their level of difficulty, thus fulfilling a first condition for the adaptive design of future training sessions. As expected, the number of cuboids of a figure were found to be a difficulty-determining characteristic. However, it should be critically noted that there was no high correlation between the complexity of the figure and the difficulty of the task. This was partly due to the fact that the complexity variation of the figures was quite limited: there were only figures with three, four, five, or six cuboids. On the other hand, there were other difficulty-determining features (the rotation angle of the tasks, among others) which were not considered in the evaluation due to the small number of items and the unsuitable task. These findings also correspond to the results of Steiff et al. (2018) who showed that the complexity of the MRT stimuli increases with an increasing number of axes.

When discussing the adaptability of the training environment, it should not be forgotten that this term is generally very broad. The adaptive environments addressed here refer to the adaptation of the task difficulty depending on the solution behaviour. However, adaptation can be done in many ways. In addition to the solution behavior, other individual characteristics of the users should be considered in software development. The adaptation of personal preferences, motivation, cognitive load, etc. could be further steps in the design of innovative learning and training environments.

Third, the connection between paper-and-pencil MRTs and virtual MRTs to validate virtual MRTs was analysed. The correlation analysis revealed a highly significant correlation. It can therefore be presumed that a VR environment can determine the mental rotation ability and can replace paper-and-pencil MRTs for future investigations. Digitally measured and stored data could be automatically evaluated and, if necessary, directly reported back to the individuals. Digital assessment opens up the possibility of making research and training environments to support MRT more efficiently by directly storing, processing, and evaluating the data and making certain adjustments if necessary. This saves time, costs, and makes the environment more flexible.

The results of the study confirm the expectations and provide subsequent results for the development of optimised VR-based mental rotation training. The training can consider the potentials of VR environments by being interactive and adaptive and by increasing user motivation through feedback.

7 Summary

This study investigated a possibility for a VR-based measurement and improvement of mental rotation ability. In addition, decisive findings were generated to develop adaptive support training. To realise this, a VR-based environment was designed in which a virtual MRT based on classical MRTs (Peters et al. 1995) needed to be solved by participants. Virtual figures were designed with different degrees of difficulty by manipulating the number of cuboids by what were *a priori* assumed difficulty determining attributes. The virtual sequence was divided into two phases. In the first phase, the virtual mental rotation ability was recorded, while in the second phase, the participant was trained by the additional interaction possibilities with virtual figures. At the beginning and at the end of the investigation, the mental rotation ability was measured by using paper-and-pencil MRTs to identify possible training effects. The investigation aimed to answer the following questions:

- How does the virtual phases affect the mental rotation ability?
- How do difficulty-determining feature assumed *a priori* (the number of cuboids of an item) correlate with IRT-based difficulty determination of the tasks?
- How is the MRA measured by paper-and-pencil MRT related to the MRA measured by virtual MRT?

The results of the study confirmed the expectations and showed that MRA improved after the virtual phase. Furthermore, the findings reveal that the difficulty of virtual MRT items is related to the complexity of the figures (number of cuboids) and that the paper-and-pencil test based MRA is highly correlated with the MRA measured by virtual MRT. As a next step, the findings of the study should be incorporated into the development of an adaptive training environment of the MRA.

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