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Cognitive Modifiability in 3D-IVR and 2D Computerized Environments: The Effects of Rotation of Information Resources and Shift of Viewing Angles

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Abstract: Research findings indicate that cognitive achievements are significantly improved by practice of cognitive abilities in the 3D Immersive Virtual Reality (3D-IVR) environment. The current study focuses on the effects of two spatial characteristics of the computer environment, Rotation of Information Resources (RIR) and Shift of Viewing Angles (SVA), on cognitive modifiability as measured in a dynamic assessment (DA) procedure. The DA was composed of modified versions of the Analogies Subtest (AN) from the Cognitive Modifiability Battery (CMB) adapted for the computerized environment and includes pre-teaching, teaching, and post-teaching phases. The analogies contain dimensions of color, number, height, and position. In the teaching phase, children mediated various problem-solving strategies. The sample was composed of children in Grades 1 and 2 (n = 73). They were randomly assigned to either 3D-IVR or 2D conditions. Higher frequency of use of SVA contributed significantly to pre- to post-teaching improvement of analogical thinking. Higher improvements were found in dimensions of height and position than in color and number. The dimensions of height and position are specifically connected to spatial perception, hence the higher improvement. The findings are explained in relation to the importance of the use of SVA and RIR as crucial spatial characteristics for developing cognitive maps formation, and cognitive performance.

Keywords: dynamic assessment; cognitive modifiability; computerized environment; Immersive Virtual Reality (IVR)

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1. Introduction

The spatial characteristics of computerized environments seem to be crucial for enhancement analogical thinking in 3D-Immersive Virtual Reality [3D-IVR] and 2D. The purpose of the current study was to investigate their effects on cognitive modifiability as measured in dynamic assessment (DA) procedure. Unlike standardized testing, DA involves an active teaching of cognitive and metacognitive strategies aimed at improving processes of perception, learning, thinking, and problem-solving. DA is aimed at modifying an individual's cognitive functions within the testing process and observing subsequent changes in learning and problem-solving patterns. The conceptualization behind using change criteria is that measures of modifiability are more closely related to mediational processes by which the child is taught how to process information than they are to static measures of intelligence. The mediational strategies used within the DA procedure have more "matching value" to learning processes in other life contexts than do conventional static methods and therefore give better indications about future changes of cognitive structures [1,2].

The current research is intimately related to sustainability from two perspectives: the theory of Structural Cognitive Modifiability and Mediated Learning Experience (SCM-MLE) and the virtual reality (VR) technology. The first perspective, the SCM-MLE theory, deals with the interaction between the individual and his/her sociocultural environment and its effects on intellectual development and cognitive modifiability. According to the SCM-MLE theory, the plasticity and modifiability of the human cognitive system are an existential dimension of human beings. Cognitive modifiability is conceived as a core element enhancing human sustainability on an intra-personal level. In a way, the concept of cognitive modifiability extends the concept of sustainability to the personal level, beyond the natural and social domains. According to this view, the individual is perceived as an open system influenced by previous experiences that affect his/her cognitive development and the capacity to adapt to changing situations. The SCM-MLE theory has led to a new conceptual formulation of intelligence, which is conceived as plastic and changeable rather than a fixed entity [1]. The second perspective is VR technology, which is a sustainable learning technology. From a social point of view, VR technology is accessible to people all over the world and requires only a basic personal computer and simple VR googles. From an ecological point of view, it does not consume physical resources (such as paper or plastic) and saves the need to transfer physical learning products. Looking at the learning process, developing virtual learning environments saves the need to create a physical learning environment. Virtual learning environments are characterized by visual richness, content, and possibilities, therefore allowing innovative learning opportunities that do not exist. In addition, understanding the cognitive modifiability process combined with the effects of VR in educational settings is important, since it can contribute to teaching, simulating, and experiencing sustainability issues among children and adults.

Previous research indicates that the 3D-IVR environment, used synergistically with a DA procedure, helped children to internalize abstract analogical operations and use them in the future in more complex problems than those presented in 2D and non-computerized conditions [3]. However, the specific characteristics of the computerized 3D-IVR and 2D environments during DA that were found to affect cognitive modifiability were not clear. In the second phase of this research, reported in the current study, we asked how use of specific characteristics of computerized environment enhance cognitive modifiability. The spatial characteristics examined in our study were the extent of using rotating information resources (RIR) and the number of shifting viewing angles (SVA) imbued within the information resources.

Based on previous studies [4–14], we hypothesized that by combining problem rotation and observing the information from different angles, the extent of visual information gained from these characteristics would positively influence children's cognitive modifiability, and that using these characteristics in a 3D-IVR environment would have more impact than in a 2D computerized environment.

Before addressing the details of this study, we discuss (a) the Mediated Learning Experience theory (MLE; Feuerstein), [1,2,15–17], which serves as a basis for our DA approach in this study, (b) the DA of learning potential, (c) the effectiveness of DA in computerized environments, (d) the unique characteristics of 3D-IVR technology, (e) measurement of VR characteristics, (f) spatial characteristics of the computerized environment—RIR and SVA, and (g) the importance of training analogical reasoning, which is the cognitive operation used in our DA device.

2. Mediated Learning Experience (MLE) Theory

MLE interactions are defined as interactions in which parents, siblings, peers, or DA examiners interpose themselves between the presented information and the learner and change the stimuli for the developing child so that the strategies and information can be absorbed and internalized [15,16]. As children gradually internalize the strategies and information, they become integrated mechanisms of change in their learning and thinking activities. The internalized strategies and information allow developing children in the future to use them independently without relying on external mediation to benefit from novel learning experiences, use the self-mediation process, and modify their own cognitive system. Feuerstein suggested 12 criteria of MLE; however, only the first five were operationally developed in educational and developmental research [16–23]. For a more detailed description of the SCM-MLE theory, readers are directed to the literature [15,17].

Interactions saturated with MLE strategies assist children to internalize learning mechanisms and develop self-mediation strategies. Efficient MLE interactions were found to enhance changes of cognitive structures, remediate deficient cognitive functions, and afford the means to benefit in the future from MLE in other learning contexts. According to the SCM-MLE theory, cognitive modifiability cannot be estimated by previous learning experiences or standardized tests. An important derivative of the SCM-MLE theory is the DA approach, which focuses on the learning process and the individual's ability to modify his/her cognitive functions.

3. The DA of Learning Potential

The DA of learning potential is a relatively novel approach to assess the individual's learning skills, learning potential, and metacognitive functions. DA has emerged because of the inadequacy of standardized testing in evaluating a child's learning potential, as well as the lack of information on deficient cognitive functions, that are responsible for cognitive modifiability, low academic achievements, and low standardized test scores. The emphases in DA are on assessment of the child's ability to change cognitive functions, with the support of an examiner who intercedes within the test situation to modify the child's performance. During the DA process, the examiner observes the improvement in cognitive functioning as an indicator of the child's cognitive modifiability in the future. The problem with standardized tests lies not in what they do, which they do very well, but instead in what they do not do. Standardized static tests reveal the manifested level of the individual's achievements, without any attempts to mediate to assess cognitive modifiability. In the current study, we use the DA approach that is based on Feuerstein's SCM-MLE theory [15] as applied to young children by Tzuriel [1,2,16,18,24].

Tzuriel's [1,2,16–18,20,24] DA approach includes specific unique characteristics that are applicable to early childhood. These characteristics refer to diagnostic resources, mediation processes adapted to the child's developmental stage, specific assessment techniques, and novel DA instruments adapted for early childhood. Tzuriel's DA instruments and assessment procedures are based simultaneously on three dimensions: (a) dimension of task characteristics such as type of cognitive operation (e.g., analogy), (b) dimensions of the learner such as deficient cognitive functions (e.g., impulsivity, lack of verbal tools) and non-intellective factors (e.g., intrinsic motivation, accessibility to mediation), and (c) the dimension of mediation processes such as specific metacognitive strategies, mediation for meaning, mediation for transcendence (e.g., expanding of rules and generalizations), and mediation for feelings of competence (e.g., rewarding). The task's dimensions are focused on materials appropriate to early childhood and include colored tangible blocks, cylinders, cards with pictures, and plates with game-like characteristics. The emphasis of the DA is on cognitive changes, mediation strategies, and metacognitive processes rather than on the fixed end-result that characterized the standardized tests. The DA tasks vary along levels of complexity, novelty, and abstraction. In the clinical version of DA [1,2,24], the characteristics of the child being assessed refer not only to cognitive aspects, but also to non-intellective factors (e.g., intrinsic motivation, anxiety, frustration level), which are known to affect the child's cognitive processes.

The current study was conducted using the measurement/research version of DA [1,2,18,24]. The measurement/research version includes three testing phases: pre-teaching, teaching, and post-teaching. As a rule, a preliminary baseline stage is administered before testing to familiarize the child with the dimensions of the test and with problem-solving strategies. The pre- and post-teaching phases are comprised of parallel problems. In the teaching phase, the child is mediated how to apply efficient strategies to solve problems, specific verbal tools, and executive functions such as self-regulation and working memory strategies. The child's pre- and post-teaching achievements are scored. The pre- and post-teaching improvement indicates the level of cognitive modifiability. In the present research, we used the AN Subtest from the Cognitive Modifiability Battery (CMB) to assess children's cognitive modifiability [25,26]. We measured the overall score of the problem-solving as well as the score in each of the four dimensions of the analogies: height, color, number, and position. The easy problems contain few dimensions as opposed to the difficult problems, in which the child is required to deal simultaneously with more dimensions and higher levels of abstraction.

4. The Effectiveness of DA within Computerized Environments

The goals of the current study were (a) to investigate the effect of mediation of analogical thinking on cognitive modifiability of children within a DA procedure in a computerized environment and (b) the effects of spatial characteristics of the computerized environment. Studies have indicated that development of cognitive abilities among children while using computerized environments led to better cognitive achievements [27], and significantly improved cognitive achievements while practicing cognitive abilities in a 3D-IVR environment [5,9,10,12,28].

A VR environment is characterized by creating an experience of presence. The subject feels as if he/she is immersed in the computerized environment he/she is interacting with. The VR environment allows much more efficient learning of abstract concepts and multiple points of view than in the real world. The VR environment characteristics might empower processes such as teaching and assessment during the DA procedure. The characteristics we examined in the current study were the extent of using rotating information resources and the number of shifting viewing angles (perspectives) of the information resources (see below). Our assumption was that by combining problem rotation and observing the information from different angles, within a DA procedure in a computerized environment, we enhance the child's cognitive processing of analogical reasoning.

5. The Unique Characteristics of 3D-IVR Technology

5.1. Immersion in the Environment

An important characteristic of virtual reality (VR) is that it creates immersion in the environment. This is a psychological state characterized by self-perception of inclusiveness and interaction in the environment, which generates a sequence of stimuli and experimentations, an environment that creates a high level of immersion, helps in isolating the learner from the actual physical environment, and enhances his/her sense of presence (see below). Pantelidis [8] describes VR as an experience of interactive computer-based environment, where the user becomes proactive in the virtual world and is immersed therein. The VR technology presents 3D information that creates a reality inside of which the user can act, observe, move, and manipulate information. The innovative components of this tool exceed the intensity of other existing tools for expressions [4,28].

5.2. Sense of Presence

VR is a relatively new technological tool, studied mostly in the last two decades, and includes several distinct characteristics. One of the prominent characteristics of the VR environment is the sense of presence [27]. A sense of presence is a subjective experience of being in one place while being physically present in another place [28]. In other words, it refers to an individual's feeling that he/she is in the virtual world. It is an important factor influencing the quality of the virtual reality (VR) experience. In this situation, the subject feels more connected to the environment created by the computer than the environment he is situated in. VR stimulates a person's imagination causing a psychological transference of one's sense of presence to another place [29]. The sense of presence in the VR environment may come in differing degrees of intensity relating to the quantity and complexity of the factors that generate it [30].

5.3. Interactivity and Dynamics

The VR environment is characterized by 3D information that allows the user to act, observe, and move therein [11]. In the virtual space, the user can lift and move blocks, rotate information resources, and observe them from different perspectives. Hence, the type of learning in the VR is active/experiential [11]. Active learning is related to the Experiential Learning Theory (ELT), [31,32] and came to the fore in this study among other things. Our assumption is, in line with the ELT theory, that the information gathered through spatial characteristics of the computerized environments are gradually transferred to reflections and abstract concepts.

6. Measurement of VR Characteristics

Throughout the years, several approaches and tools have been developed to measure variables such as the feeling of presence, immersion in the environment, and interactivity [29,30,33]. The main measurement used in most of these studies has been based on users' subjective reports in the VR [30]. For example, sets of measurable factors were categorized to measure involvement and immersion in the experimental process in the VR environment. These factors are user's perception of the degree of control in the task, sensory factors that stimulate all the senses simultaneously, distraction factors such as isolation from the physical environment, focus and awareness of the interface, and the scene's realism. Along with the subjective measurement, a need for tracing objective measurements of the phenomenon of presence has emerged, for example, assessment of physical measurements altered while being situated in the VR environment. It was proposed to quantify physiological measurements by EEG and fMRI. Studies conducted with EEG pointed to connections in neural activity; however, researchers found these findings difficult to interpret [30].

Another approach was based on measuring responses such as facial expressions, reflexes, behavioral measurements (e.g., active search by using different perspectives), number of errors, transferring the ability to the real world, and speed of response [33].

7. Spatial Characteristics of the Computerized Environment: RIR and SVA

In the present study, we adopted the behavioral measurement approach of presence. We focused on specific users' movements in the VR environment since they are tangible and can be measured. These measures are unique to the computerized environment and contribute to the ability of the participant to explore and solve the analogy problem in the virtual environment. The behavioral measures we used include the extent to which the participants used the two spatial characteristics of the computerized environment: Shifting Viewing Angles (SVA) and Rotation of Information Resources (RIR). Both characteristics might broaden the range of observation and the ability to explore the information available in the VR environment, which contributes to enhancing problem-solving. Visual–spatial ability helps individuals to understand maps and diagrams and evaluate visual aesthetics. Piaget described spatial intelligence as an integral part of the individual's development in which a motor-sensory understanding of the space is created in infancy and evolves throughout the years [34].

7.1. Rotation of Information Resources (RIR)

Mental rotation is considered as an important cognitive operation of spatial thinking and a fundamental task in cognitive science research [35–37]. It involves imagining the movement of objects external to our bodies. Shepard and Metzler [38], in their classic research, found that participants' reaction to problems involving 3D shapes was linearly related to the size of the angle of rotation. They interpreted this result as a process of a mental rotation of the physical world.

Mental imagery, which is intimately related to mental rotation, is an experience that clearly represents a perceptual experience. A central theory in the field of mental imagery is the dual coding theory (DCT) [39], which explains the process of generating mental imagery. The source of the images is connected to the activity of two different sub-systems:

one is verbal and focuses on language, and the second is related to imagery and focuses on non-verbal objects and events. In the current study, the computerized environment provides unique non-verbal stimuli, which enhance the information gathered in the process of generating mental imagery. Mental imagery is not merely a reconstruction of perceived objects and events; it can also be the product of perceptual information that was stored in the memory and underwent various processing. Mental imagery is not one distinct cognitive activity, but rather a collection of abilities (e.g., imagining of shape, color, and rotation) [40].

Mental imagery was found in several studies as a central cause of memory improvement, problem-solving, and rotation ability [38,39,41]. It is noteworthy that thus far, only a few studies have examined the connection between rotating various information resources in a VR environment and different cognitive abilities. Merickel [6,7] studied the cognitive operations that are associated with children's ability to solve spatial problems within a computerized interface or 3D-IVR. The mental rotation tasks require an ability to visualize, displace, and transform shapes through mental imagery. The findings showed that children's ability to perform spatial tasks in a 3D-IVR environment was associated with cognitive skills of creating, operating, and utilizing mental imagery. In another study, rotation training of 3D objects in a VR environment was found to influence thinking flexibility of children with hearing impairment [9]. The researchers developed an intervention program designed to improve formal inductive reasoning and thinking flexibility of children with hearing impairment aged 8–11 through practicing rotation of 3D objects in a 3D virtual Tetris game.

7.2. Shifting Viewing Angles (SVA)

Another characteristic of VR in a computerized environment is the possibility to observe information by shifting fixed viewing angles. Perception from different perspectives enables reflection and substitution of a new visual space, otherwise non-existent in the real world [4,8,14,27]. For example, in a study on the effect of 3D-IVR environment on understanding of abstract concepts, the researchers found that experiencing different perspectives in a 3D-IVR broadened the observation and contributed to the learning and internalization of abstract and multi-dimensional concepts [14]. Consequently, Dede [33] concluded that VR allows the possibility of broadening the viewing angles in the task and its derivative reflection by shifting additional perspectives, non-existent in 2D and in reality. Dede makes a distinction between "egocentric" and "exocentric" perspectives. The egocentric perspectives refers to how an object, space or phenomenon appears from the inside, as opposed to an exocentric perspective, which refers to viewing them from the outside. Each angle provides different information regarding the information resources. Dede [33] claims that the ideal learning is bi-centric, which combines the use of all perspectives. It was further found that the exocentric perspective enhances spatial perception regarding the situation or the problem and enables a consolidation of insights stemming from the user's distance from the context.

In the current study, we designed a computerized environment with three fixed viewing angles The first is the exocentric angle from which the child can observe the problem from above; the second is the side angle, observing the problem as if standing next to it at eye level; and the third is the inside angle, whereby the child is situated at the center of the board where the problem is placed and observes the blocks representing the analogical thinking problem. We hypothesized that children who shifted more viewing angles would achieve higher cognitive performance as compared with children who shifted them to a lesser degree. In addition, we hypothesized that this effect will be manifested particularly in the problem dimensions associated with the spatial dimensions, namely, position and height (see Method). It is worth noting that to the best of our knowledge, there are no studies that indicated the contribution of RIR and SVA in a 3D-IVR environment on cognitive modifiability in DA.

8. Analogical Reasoning

The operation of analogical reasoning in the current study as the main cognitive operation of thinking was chosen due to its centrality for children's cognitive development [42–45]. Analogical reasoning was found as central operation even with children at the ages of three and four years old, though they fail to reach a high level of ability until they have entered maturity [45,46]. Despite the consensus that analogical reasoning is central to a child's cognitive development, researchers disagree about the mechanism involved in developing analogical reasoning. Over the years, several theories have emerged to explain the development of analogical reasoning [18,36,44,46–56].

According to Piaget, the ability to reach conclusions about relationships starts to develop at the age of seven years but matures as a complex formal operation at ages 11 to 12. At that age, children start to solve abstract problems, which require classification of objects, ideas, or persons into groups. The ability to classify indicates an ability to understand the associations between objects or entities in a group. Understanding of these associations leads consequently to the development of new relations between these objects or entities. The comprehension of identical components and their relations enables the development of understanding of classical analogies in the format of A:B :: C:D. The capacity to process high-order analogy according to Piaget develops in the formal operations stage, around the ages 11 to 12.

Two theories have derived as competitive branches of Piaget's theory: The Relational Primary Theory [50] and the Relational Shift Theory [44]. Unlike Piaget's approach, Goswami [49] argued that the child's level of analogical reasoning does not depend solely on his/her age. The child's difficulty to understand the relationships between terms does not derive necessarily because of the difficulty in coping with the process of reasoning. According to Goswami, analogical reasoning development depends on continued development of a store of knowledge. It starts from a young age and continues to develop with widening of the knowledge store of relevant relationships in the individual's disposal.

Similarly, Gentner [42] suggested that a child's analogical reasoning develops when individuals experience change and transition in relationships. In the first stage, children explain the analogy in terms of the similarity between objects and/or traits. As children become progressively older, they gradually move to reason based on relationships. The literature is replete with evidence showing that increase of executive functions such as self-regulation and working memory contribute significantly to analogical reasoning capacity in children [55,57,58] and adults [59]. Researchers suggest that the development of analogical reasoning depends on the interplay among relational knowledge, the capacity to integrate multiple relations, and self-regulation of featural distraction [55].

9. DA Using Analogical Reasoning

Several researchers focusing on analogical reasoning reported that a methodical process of learning how to solve analogies can be applied with young children [60–63]. For example, it was reported that five to six years old children at age solved analogical problems on a much higher level after a short intensive phase of teaching within a DA procedure than what could be expected from children of that age [1,22,26]. It was also reported that mediation how to solve analogies relevant to children and based on familiar relationships and concrete imaging significantly improved children's performance [55]. In another study it was found that prior learning experience with analogical reasoning was transferred to spontaneously solving other analogical problems even weeks later [63].

In the present study, our focus was on the relation between the spatial characteristics of the computerized environment and pre- to post-teaching improvement (within a DA procedure). The improvement level indicates the level of cognitive modifiability in analogical reasoning. We measured the overall score as well as specific scores on each of the test's dimensions (color, number, height, and position).

10. Hypotheses

Hypothesis 1. *Children in the 3D-IVR group will show higher pre- to post-teaching improvement on the analogies than children in the 2D group.*

Hypothesis 2. *Children who will use more Rotation of Information Resources (RIR) and Shifting Viewing Angles (SVA) will demonstrate higher pre- to post-teaching improvement on the AN subtest than children who will use less RIR and SVA.*

Hypothesis 3. *The effect of RIR and SVA would manifest itself in the performance related to the problem dimensions of height and position associated with spatial perception more than in other test dimensions. The rationale for this hypothesis is that height and position are intimately related to the spatial characteristics of rotation of the objects (blocks) and shifting of angles. On the other hand, the impact of the computerized environment on dimensions of color and number is similar in 3D-IVR and 2D modes.*

11. Method

11.1. Participants

The sample included 73 children—33 girls and 40 boys. The sample was drawn from first and second grade classes from two elementary schools. The schools were in two middle-sized cities. Parental consent was asked when recruiting the sample. Out of 93 parents, 73 parents approved their children's participation in the study. The children's ages ranged between 6–8.5 years (M = 90.00, SD = 6.88). The sample was divided randomly into the 3D-IVR and the 2D groups. The sample did not include children with learning difficulties. The group by gender composition is presented in Table 1. No significant group by gender composition was found, $\chi^2 = 0.75$, df = 1, *ns*.

Table 1. The groups by gender composition of the sample.

Group	Boys		Girls	
	N	%	N	%
3-D IVR	19	52. 7	17	47.2
2-D	21	58.3	15	41.7
Total	40	54.8	32	45.2

11.2. Measures

11.2.1. The Analogies (AN) Subtest

The purpose of the AN Subtest from the Cognitive Modifiability Battery (CMB) is to evaluate the cognitive modifiability in analogical reasoning of young children [2,18,25]. The CMB was originally designed for pre-school to fourth grade students but was extended later to be used with children with learning difficulties in the fifth through eighth grade. The assessment procedure is based on the SCM-MLE theory [64] adapted specifically for young children [2,24]. In the current study, the AN Subtest was transformed to computerized version (see details below).

The original test consists of a wooden board (18 × 18 cm) with 9 "windows" arranged in a 3 × 3 format and 64 colored blocks arranged by four colors (red, green, yellow, and blue), and four heights (2, 3, 4, and 5 cm). In a regular format of testing the examiner places block(s) in three windows (top-left, top-right, and bottom-left) and asks the child to complete the blocks in the vacant fourth window (bottom-right). The AN Subtest includes a baseline-preliminary stage aimed at familiarizing the child with the test dimensions and basic rules of analogical problem-solving. In Figure 1, an example of a problem in a Virtual Board is presented.

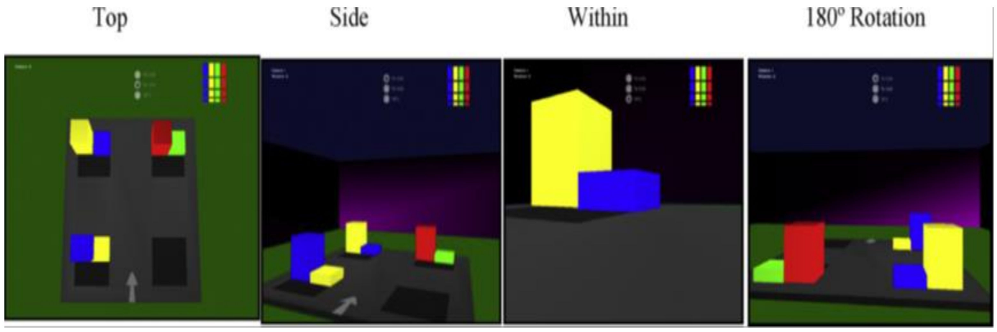

Figure 1. Representation of a problem (TR2-B) in a Virtual Board as seen from different angles and rotation (adapted from "Improving children's cognitive modifiability by dynamic assessment in 3D Immersive Virtual Reality environments," by D. Passig, D, Tzuriel, & G. Eshel-Kedmi, 2016, Computer & Education, 95, pp. 296–308. Copyright 2016 by Elsevier).

The problems of the AN Subtest are organized in an ascending order of difficulty, as the number of transformations in each problem increases. The position dimension is the most difficult one.

The DA procedure includes three phases: pre-teaching, teaching (mediation), and post-teaching. The level of improvement from pre- to post-teaching phases indicates the child's cognitive modifiability. In the pre- and post-teaching phases, the examiner places the blocks over the plate to create the problem, while the child observes their construction. No mediation is given at these phases, except for small prompts (e.g., "Look in both directions", "Don't rush", "Check your answer one more time").

In the teaching phase, carried out for about 30 min, the examiner mediates the child how to systematically explore the problems' dimensions and understand the transformation rules of the analogies, non-verbal focusing, self-regulation of behavior, verbal anticipation of the solution, simultaneous consideration of the test's dimensions, rhythmical intonation of contents, direct teaching of the transformation principles, and improvement of performance efficiency (as reflected in investment of time and efforts). Two total scores can be extracted: pre-teaching and post-teaching. Each score is composed of the sum score of the dimensions of color, height, number, and position of the AN Subtest. The maximal score of each dimension is 14, and the total possible score is 56. Cognitive modifiability is indicated by the level of improvement from pre- to post-teaching. Cronbach alpha reliability coefficients for the pre- and post-teaching phases were 0.78 and 0.83, respectively [31].

11.2.2. Computerized Version of the CMB AN Subtest

Two computerized versions of the AN Subtest were developed specifically for the current study: (a) 2D multimedia computer application using a screen and mouse interface and (b) 3D Immersive Virtual Reality (IVR) version using a Head Mounted Display interface (HMD). The starting screen includes a squared flat board with four black cut-out windows positioned at the top-left, top-right, bottom-left, and bottom-right corners. A pile of virtual blocks for construction of the solution of the analogies are presented as a storage bin at the top-right corner of the screen. The storage bin includes four vertical rows of blocks in different colors: blue, green, yellow, and red, arranged by height (from highest to lowest total 4 blocks for each row). In the front section of the board, which is the closest to the child, there is a sign of an arrow that gives the child a reference point to the bottom side of the problem.

The storehouse of the original tangible test includes 64 wooden blocks. In order not to spread too many virtual blocks in the VR environment, we designed an option that by pressing on the block in the storehouse, the participant receives four other blocks of the same color, as in the original wooden version. In constructing the VR environment, two spatial characteristic applications to the computers' environment were added: (a) *Shifting Viewing Angles (SVA)* and (b) *Rotation of Information Resources (RIR).*

The computer program spatial characteristic included two applications: a possibility to observe the problem from three different points of view—above, side, and inside—as if the participant stands in the middle of the board and observes the blocks around. The starting point is from an above perspective and the participant could shift from one perspective to another by pressing on one of the three buttons located in the middle-top of the screen. In addition, the participant can turn the problem on a 360° horizontal axis and at an angle of 45° on a vertical (up and down) axis. These options allow observation of the analogy from a variety of perspectives. The participants are given the possibility of shifting between the viewing angles while observing the information resources. This possibility enables a virtual representation of the problem from different perspectives. These shifts were found to contribute to the learning experience (e.g., Salzman et. al., 1998; Dede, 2005). The computer program automatically quantifies the number of shifts of viewing angles and the number of rotations of information resources and automatically produces an index of these two measures for each item and total scores for the pre- and post-teaching phases.

During each phase of the assessment, the student could observe the problem through both SVA and RIR features. During the teaching stage, and in addition to the mediation of principles of solving the analogies, the examiner could shift between viewing angles and rotate the problem to display the principles of the analogy problem-solving. For example, for the purpose of demonstrating the transformation of height dimension, it is possible to show the problem to the student from the above and the side angles, thereby illustrating the transformation of heights. For demonstrating the transformation of position, rotation of the problem is demonstrated by stirring the blocks from position A to position B, thus illustrating the way in which the problem looks different from each perspective. Additionally, the examiner may mediate by giving prompts ("which block is taller?"). Following the student's answer, the examiner may show the answer visually by shifting the viewing angles. The shift in viewing angles also supports in illustrating the number dimension involved in the problem: it was possible to see the addition or subtraction in the number of blocks. The participant was given the possibility of being active in the virtual space by choosing and placing the blocks, rotating the problem, and shifting the viewing angles of the problem. In sum, the computerized test version yields two spatial characteristic measurements: (a) observing the problem from different perspectives and (b) rotating the problem. Both characteristics were automatically measured before and after the teaching phase to provide indications about changes in number of RIR and SVA.

11.3. Pilot Study

To test the applicability of the hardware and software for the use of first and second grade students, we first conducted a pilot study on a sample of children (n = 12) in first and second grades. Based on the insights from the pilot study, we consulted with a virtual reality expert about the technical aspects of the interface. "Virtual walls" were added to the board framework and created "an atmosphere" of a room. The walls were painted in different colors and the angle of the light illuminating the space changed accordingly to the spatial movements. Subsequently, the children tested reported an enhanced sense of immersion and easier orientation in space. The interface of the tested children with the computer application improved the ability to move the blocks and enlarge them, to use more rotation options of the board (i.e., a two-way rotation and up/down movements), the side angle was improved to an angle that enabled the observation of the dimension of height (in addition to the dimensions of color and position), and the blocks' contours were emphasized. The icon that enabled a shift in viewing angles was enlarged to make it easier to identify and activate it. The icon of an arrow, which indicated the location of the mouse in the space, was changed to a hand-shaped icon. In the preliminary study, we used a 3D-IVR helmet. However, the use of the helmet was technically cumbersome and posed difficulties for the children both physically and cognitively. Therefore, it was decided to use a Head Mounted Display (HMD) device instead. The HMD device created an immersive VR effect like the helmet device, but with better reception and greater comfort.

Learning about the child's adjusting process to the virtual environment, a structured process of 10 min familiarizing stage was added to let the child experience the computerized environment prior to the test. This stage included an introduction and familiarization with the HMD, experiencing basic other 3D environment and movement directions (e.g., up-down, left-right, changing perspective, and degree of rotation), exercising the selection of blocks from the storage bin, and moving them to locations on the digital board.

The program included (a) a Dell laptop in which the Quest 3D 3.0 program was installed, (b) a mouse connected to the computer by which the children navigated in the virtual world, and the (c) the HMD in the 3D-IVR.

11.4. Procedure

In the first phase, all children were administered the pre-teaching for 30 min. In the second phase, children in the two groups were mediated to solve the analogies for 30 min and in the third phase all children were administered a parallel test of the analogies. The 3D-IVR and the 2D groups used the same modality of presentation in all three phases. The research design is presented in Table 2.

Table 2. The design of the study.

Group	Pre-Teaching	Teaching	Post-Teaching
3D-IVR (n = 36)	Analogies SVA, RIR	+	Analogies SVA, RIR
2D (n = 36)	Analogies SVA, RIR	+	Analogies SVA, RIR

The DA was performed in a quiet room assigned by the school. Only one child was assessed successively. The DA meeting included three stages, according to the CMB AN subtest procedure: pre-teaching, teaching, and post-teaching. Before starting the assessment, the examiner (in both study groups) introduced himself/herself to the child and familiarized him/her with the CMB-AN subtest dimensions and problem-solving principles (i.e., dimensions of height, number, color, and position, and analogy transformation rules, see Tzuriel [30]). The examiner explained the mouse–screen interface and introduced the child to the features that enable the moves and the blocks' selection. In the 3D-IVR environment, the examiner also guided the child on how to use the Head Mounted Display (HMD) and on how to navigate and orient oneself in the 3D-IVR space. It is important to emphasize that the teaching stage within the DA process was conducted similarly with both groups (i.e., the mediation strategies used by the examiner with each child were the same). The main group differences in performance could be attributed to the type of environment (i.e., 2D versus 3D-IVR).

12. Results

12.1. Pre- to Post-Teaching Gains on the AN Subtest in the 2D and 3D-IVR Groups

A preliminary analysis was carried out to examine Hypothesis 1. To examine the pre- to post-teaching improvement in performance scores, we applied repeated measures MANOVA of Group × Time (2 × 2). The analysis revealed a significant Group × Time interaction, $F(3,113) = 25.15$, $p < 0.001$, $\eta_p^2 = 0.40$. This finding indicates, as expected, that the improvement of the 3D-IVR group was significantly higher (Pre, M = 2.58, SD = 3.27; Post, M = 10.72, SD = 3.89) than the improvement of the 2D group (Pre, M = 4.02 SD = 3.36; Post, M = 9.75 SD = 2.87). This finding supports Hypothesis 1.

12.2. Pre- to Post-Teaching Gains on the AN Subtest as a Function of VR Characteristics (RIR and SVA) in the 2D and 3D-IVR Groups

To examine Hypothesis 2, we divided the participants to two groups (low versus high) according to the median score on RIR use or the SVA use, respectively. Two repeated measures ANOVA were carried out for each variable: Treatment × RIR Group × Time

(2 × 2 × 2) and Treatment × SVA Group × Time (2 × 2 × 2). The findings reveal only a significant interaction of SVA Group × Time, F(1,68) = 10.64; $p < 0.01$, $\eta_p^2 = 0.14$. This interaction indicates that the improvement of the High SVA group was significantly higher (Pre, M = 3.08 SD = 3.43; Post, M = 11.23 SD = 2.26) than the improvement of the Low SVA group (Pre, M = 3.58 SD = 3.33; Post, M = 9.06 SD = 3.28). This finding supports Hypothesis 2 only for the SVA variable.

Simple effect analyses showed that both High SVA, $F(1,38) = 240.86$; $p < 0.001$, $\eta_p^2 = 0.86$, and Low SVA, $F(1,32) = 101.74$; $p < 0.001$, $\eta_p^2 = 0.76$, groups improved their performance significantly from pre- to post-teaching. Comparison of the Low and High SVA groups in the pre- and post-teaching phases showed that the difference between the two groups was not significant in the pre-teaching phase, $F(1,68) = 0.16$, $p > 0.05$, but becomes significant at the post-teaching phase, $F(1,68) = 9.51$, $p < 0.01$, $\eta_p^2 = 0.12$.

12.3. The Relation between the Spatial Characteristics of the Computerized Environment and the Cognitive Performance in Each of the Test's Dimensions

According to Hypothesis 3, the effect of RIR and SVA would manifest itself in the performance related to the problem dimensions of height and position associated with spatial perception more than in the other test dimensions of color and number. To examine the effects of these characteristics, we applied a separate repeated measures MANOVA for each of the RIR and SVA characteristic. We used the median to divide the sample into High versus Low SVA and High versus Low RIR. The first MANOVA was Treatment × SVA × Time (2 × 2 × 2), where the first two variables were between-factors and the last variable was a within-factor (pre- versus post-teaching). The findings are presented in Table 3. No significant interaction was found for the RIR variable.

Table 3. Means, standard deviations, and F statistics for each an subtest dimensions according to sva level in pre- and post-teaching test phases. (Reprinted by permission from T. Oon-Seng, C. Bee Leng & I. Wong Yuen Fun (Eds.). *Advances in mediated learning experience in 21st century education* (pp. 73–96). Singapore: Cengage Learning Asia).

Dimension	**Low SVA**		**High SVA**		**SVA × Time**	
	Pre	**Post**	**Pre**	**Post**	***F*(1,68)**	η^2
Height	9.54	10.78	9.30	12.64	5.93 *	0.08
Position	9.45	11.57	9.25	12.64	4.01 *	0.06
Color	11.21	12.75	10.51	13.66	1.98	0.03
Number	11.60	12.57	11.23	13.41	3.08	0.04

* $p < 0.05$.

Table 3 shows significant interactions of SVA X Time only for the dimensions of height and position. These findings support Hypothesis 3. The significant interactions are presented in Figure 2.

Figure 2 shows clearly that the improvements on height and position dimensions were higher for participants using high level of SVA than for participants using low level of SVA. Post-hoc analyses of height dimension showed that the improvement was significant for the High-Shifting group, $F(1, 32) = 34.30$, $p < 001$, $\eta_p^2 = 0.47$, as compared to nonsignificant improvement for the Low-Shifting group, F(1, 32) = 3.77, $p > 0.05$, $\eta_p^2 = 0.11$. Post-hoc analyses of position dimension showed that the improvement was significant for both High-SVA group, $F(1, 32) = 50.64$, $p < 001$, $\eta_p^2 = 0.57$, and Low-SVA group, F(1, 32) = 24.30, $p < 0.001$, $\eta_p^2 = 0.43$.

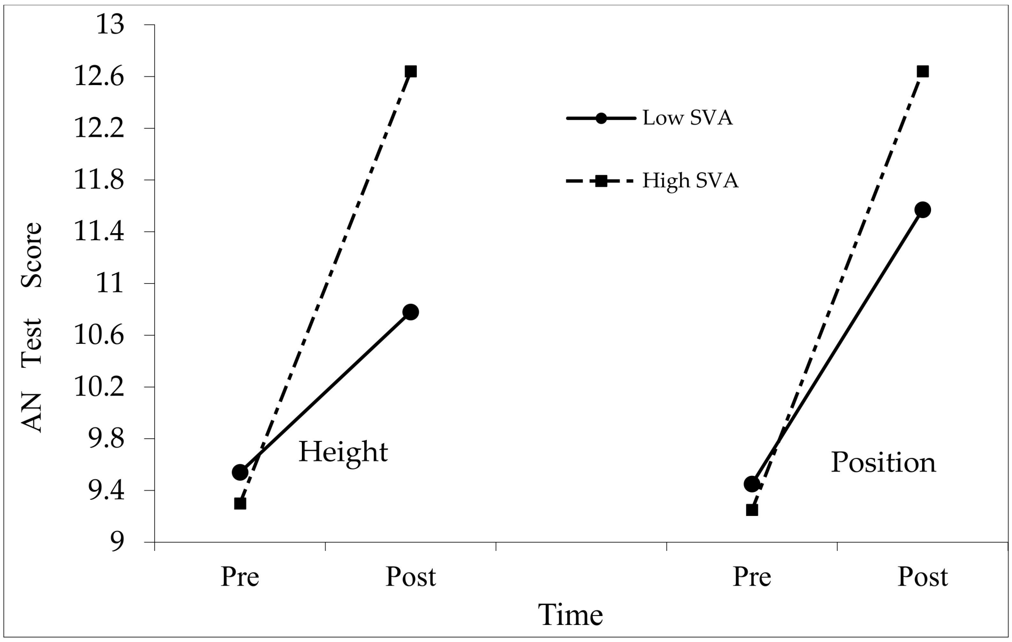

Figure 2. Pre- and post-teaching improvement of height and position dimensions of AN Test as a function of low- and high-shifting of SVA. (Reprinted by permission from T. Oon-Seng, C. Bee Leng & I. Wong Yuen Fun (Eds.). *Advances in mediated learning experience in 21st century education* (pp. 73–96). Singapore: Cengage Learning Asia).

13. Discussion

The main objective of the current study was to investigate the effect of specific characteristics of the computerized environment on cognitive modifiability of children. For that purpose, we examined two central spatial characteristics that might affect the children's performance: Rotation of Information Resources (RIR) and Shifting Visual Angles (SVA). We hypothesized that frequent use of these aspects characterizing the 3D-IVR would enhance the child's cognitive modifiability. The current study is the first known study to use computerized environments' spatial characteristics during DA and assess their impact on children's cognitive modifiability.

13.1. Hypothesis 1

In a preliminary analysis, it was found that children in the 3D-IVR group showed higher cognitive modifiability than the 2D group on analogical reasoning task, thus supporting Hypothesis 1. These findings are supported by previous research showing that children participating in a 3D-IVR condition demonstrated significantly higher pre- to post-teaching improvement than children participating in the 2D condition [3,12].

13.2. Hypothesis 2

The next step in our laboratory was to explore the contribution of the special characteristics of 3D-IVR to its superiority over the 2D condition. The findings of the current research indicated that the extent of use of SVA did not influence the initial cognitive performance, and that in both 3D-IVR and 2D conditions, it was similar. However, the findings supported Hypothesis 2 regarding the effects of use of SVA on cognitive modifiability. The RIR characteristic was not found to be as significant. Children with high SVA showed significantly greater improvement in analogical reasoning from pre- to post-teaching than children with low SVA. It seems that the use of different perspectives at the participant's-controlled shift of angles contributed to the construction of the spatial knowledge and mental model required to solve the analogy problems. It should be emphasized that during the teaching stage, the examiner mediated the participants the possibility of examining the information resources from different perspectives and thus raised their awareness and improved their ability to produce additional information from the analogy placed in front of them. It appears that the SVA characteristic combined with the mediation strategies applied in the teaching phase helped the young children to internalize the analogical operation and principles and apply their learning in the post-teaching test. According to the Dual Coding Theory (DCT) [39], it appears that the external visual stimuli deriving from the diversified observation of information resources were absorbed by the participants and converted to internal images that expanded their mental image. With time, these images were retrieved from memory and contributed to the participant's ability to solve the problem. This explanation corresponds with the Vygotskian approach, according to which systematic mediation in the visual–motor domain prepares children for a higher conceptual achievement [64]. Similarly, Feuerstein [15] and Tzuriel and Klein [60] showed that a systematic mediation of self-regulation, systematic exploratory behavior, provision of verbal tools, and comparative behavior helped students to ascend to the level of analogical reasoning in various modalities. Karpov and Gindis [64] also seem to view the transition to a higher cross domain cognitive level as a criterion of cognitive modifiability. In their research, they operationalized children's transition from visual motor to visual imaging to the symbolic level of problem solving as a criterion for cross-domain nature of cognitive modifiability.

Another possibility of interpreting the findings of this study is related to the active learning theory, according to which the process of learning is constructed on the basis of an active experimentation, e.g., [11,31,65,66]. Computerized worlds are characterized by "interactivity", which by nature enables the user to act, observe, and move within them [67,68]. The findings of the current study reinforce the notion that the more active children are in the computerized environment, the more they can implement the strategic principles to solve analogical reasoning problems. It is worth noting though that the mechanism that "translates" conceptual processes required for analogical thinking is still not clearly understood.

Our findings are like those reported in earlier studies showing that observing information resources from different viewing angles in a 3D-IVR environment contributed to expanding the viewing angle of the assignment and its derivative reflection through the use of additional viewing perspectives, e.g., [10,33]. It also contributed to the acquisition of abstract and multi-dimensional scientific concepts [14,33,69–71].

Another related concept that might explain processing of analogies is related to working memory [72,73]. Analogies require processing of complex relationships and simultaneous consideration of several changes in separate dimensions. It is possible to assume that the option given to children to observe a problem from different perspectives assisted the children in expanding their working memory by enabling them to process simultaneously the various dimensions.

13.3. Hypothesis 3

Hypothesis 3 was that the use of SVA would affect the children's performance particularly on two dimensions related to spatial perception: height and position. The findings indicated that SVA contributed significantly to improvement in solving analogies from pre- to post-teaching (see Table 2 and Figure 1), thus supporting Hypothesis 3. Height and position dimensions are known as being associated with spatial perception. It appears that the SVA expanded the external visual stimuli world to which the participant was exposed and thus formed a catalyst to reinforce the spatial perception dimensions and enhance the ability to create and activate images.

The combination of several categories of spatial space assist in constructing a cognitive map and sense of presence [71,74]. The cognitive map is composed of Figural Space and Vista. The Figural Space is the space that directly interacts with the individual, whereas the Vista is the space that is visually perceived from a certain position without movement (e.g., space of single room or town square). Environmental space is bigger than the surrounds; it cannot be perceived entirely without locomotion.

In the current study, we created different kinds of spatial information by observing information resources from different viewing angles. From the Side Angle, it was possible to see part of the problem (i.e., the Vista Space). When we shifted to the Above Angle, it was possible to see the environmental space, which was in fact the problem in its entirety. From the Inside Angle one could be “present” in the Figural Space. The Figural Space allowed participants to be situated in the center of the problem and interact directly with the blocks next to them. The possibility of SVA in the space enabled the participant to observe the height and position dimensions from different spatial perspectives. It thus illustrated to the participants the transformation that took place in these dimensions and enhanced their capacity to construct the spatial information into a full cognitive map of the problem.

It should be noted that the analogy by nature represents a transformation in the various parts of the equation. Understating the nature of the transformation is made possible through an active gathering of information and data [11,75]. The accumulated data creates the cognitive map from which the child extricates the rule of the analogy and enables him/her to successfully solve the problem. In fact, one may say that according to the findings, a high level of use of SVA enhances even more the participant’s ability to decipher the rule that represents the analogy through formal induction and contributes to the improvement of his/her cognitive performance in analogical thinking. To sum up, it was found that higher use of SVA in a computerized environment contributed to enhancing cognitive modifiability and that this contribution was particularly evident in relation to the height and position dimensions.

14. Conclusions

DA in 3D-IVR environment is more effective for the internalization of cognitive principles (by applying them into solving more complex problems, resulting in higher cognitive performance achievements) then DA in 2D environment. Higher use of SVA in a computerized environment contributes to enhance cognitive modifiability. The contribution of higher use of SVA was particularly evident in relation to the height and position dimensions of the analogy problem. The contribution of SVA to the processing of analogies performance, which occurred in the height and position dimensions in the computerized environments, is associated with enhancement of working memory, internalization of spatial perception, and multidimensional scientific concepts. 3D –IVR environment’s technology may contribute to enhancing learners’ cognitive abilities and thinking skills, including knowledge in the field of sustainability.

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