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Developing Pre-service Mathematics Teachers' Mental Rotation Skills through Dynamic Geometry Software-Supported Instruction *

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Abstract: Spatial skills, including mental rotation, are necessary to understand, comprehend, explore and learn mathematics, but research in mathematics education points out insufficient spatial skills of pre-service mathematics teachers. In this study, the effectiveness of the instruction, designed by taking Cognitive Load Theory (CLT) as the reference frame and executed in the Dynamic Geometry Learning Environment (DGLE), was investigated. The study sample was four pre-service mathematics teachers determined by the purposeful sampling technique. Individual teaching experiment, executed in three steps (pre-evaluation— teaching sessions/instruction— post-evaluation), was used as the method. The collected quantitative and qualitative data were analyzed through content analysis. Findings showed that participants' mental rotation skills were basic or below, before the instruction. They had low mental imagery skills, inadequacies in mathematics language use, and misconceptions about rotation and its components. After the instruction, their mental rotation skills, compassing the mental rotation performance, mental imagery skills, mathematical language use, and concept schemes about rotation and its components, developed. It is recommended that cognitive loads be considered while designing instruction executed in a DGLE.

Keywords: Mental rotation skill, cognitive load theory, dynamic geometry learning environment

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Introduction

Mental rotation, one of the components of spatial ability, is closely related to other skills such as map reading, wayfinding, and problem-solving and is a central metric of spatial reasoning (Bruce & Hawes, 2015). Some researchers characterize mental rotation as a neglected area of mathematics curriculum (See Bruce & Hawes, 2015). Mental rotation can be defined: (1) performing one-step (Miyake et al., 2001) or two-step (Woolf et al., 2003) mental transformation/rotation of two- or three-dimensional (2D or 3D) objects, (2) imagining how 2D objects (or 3D solids) seem after rotated in 2D or 3D space (Martin-Gutierrez & Acosta-Gonzalez, 2017), or (3) aligning a stimulus with another referenced stimulus to decide whether the orientations of 2D or 3D objects are same (Shepard & Metzler, 1971; Jola & Mast, 2005; Fernandez-Mendez et al., 2018). Mental rotation, required to cope with moving solids and relative motions (D'Oliveira, 2004), is handled as a dynamic spatial ability (See Uttal et al., 2013). Students need mental rotation skills to understand various concepts (e.g., determining the position of a point when it is rotated about another point) in mathematics curricula and to make sense of activities performed in mathematics class (e.g., imagining the solid that forms after a piece of paper is rotated about one of its edges).

Mental rotation skill has an important role achievement in and learning of mathematics (Bruce & Hawes, 2015; Hawes et al., 2015). Mental rotation skill also has the power to predict students' mathematical performance (Hawes et al., 2015). Many studies highlight that learners' 3D rotation skills are related to performance in geometry, algebra, word problems, and arithmetic (See Wei et al., 2012; Hawes et al., 2015; Uribe et al., 2017). The developed spatial skills, including mental rotation, are necessary to understand, comprehend, explore, and learn mathematics. Mathematics teachers should have the advanced spatial skills to transfer and teach their students mathematical content better and guide their students to use their mental rotation skills.

Research in mathematics education points out that the spatial abilities of pre-service teachers, who will teach mathematics to their students at various levels, are not sufficient (See Güven & Kosa, 2008; Turgut & Yılmaz, 2012). On the other side, many studies emphasize that spatial skills, particularly mental rotation, can be developed in computer-based learning environments (See Cherney, 2008; Gecu & Cagiltay, 2015; Ozcakır-Sumen, 2018). Dynamic computer software allows students to directly manipulate geometrical solids presented on the screen by using the mouse. Students can observe the spatial relations between the objects or the parts of an object through computers and discover which spatial relations change while the others do not.

Maximum learning is possible with instruction designed according to students' cognitive and developmental levels (See Woolf et al., 2003). The contribution of computer software in geometry and spatial ability is undeniable, but students can not develop their spatial skills by self-use of computers without any effective instruction. In this study, the effectiveness of computer-based instruction, designed to develop the mental rotation skills of pre-service mathematics teachers by taking into account their cognitive loads, was examined.

Cognitive Load Theory (CLT)

Traditional instructional techniques do not consider the limitations of human cognition (Schnotz & Kürschner, 2007). Most effective instruction is that considers the cognitive architecture of humans (Schnotz & Kürschner, 2007), i.e., how the human brain learns and solves problems (Centre for Education Statistics and Evaluation [CESE], 2017). CLT suggests a technology-integrated instruction that directs students' cognitive resources towards activities to facilitate learning (See Chandler & Sweller, 1991; Taylor, 2013). CLT allows students to use their cognitive capacities at the maximum level in the learning process.

Working memory, long-term memory, schema formation, and automation form the basis of CLT. Working memory is a system where information is processed (De Jong, 2010), and its capacity is limited when dealing with new information (Paas et al., 2003). This limited capacity becomes unlimited when dealing with familiar information transferred from long-term memory holding many schemas of varying degrees of automaticity (Paas et al., 2003). Learning occurs with the formation of schemas in long-term memory and the automaticity acquisition in using the existing schemes (Schnotz & Kürschner, 2007). Schemas are structures that organize information elements (Sweller, 1994). The processed information elements in working memory are stored in long-term memory as schemas. A skilled performance is possible by combining lower-order schemas into higher-order schemas for creating more-complex schemas (Sweller et al., 1998). Well-learned information is automatically processed in working memory (Sweller, 1994), which means that more working memory capacity is available (Sweller et al., 1998). Scheme acquisition and automation enable students to deal with familiar spatial tasks and solve mathematical problems without difficulty. During processing information in working memory, three different types of cognitive load arise (Akbulut, 2014; Van Merrienboer & Sluijsmans, 2009): Intrinsic load, extraneous load, and germane load. Intrinsic load is induced by the natural complexity of the content to be learned (See De Jong, 2010; Sweller, 2010). Giving place to students' prior knowledge (Mayer & Moreno, 2003), ordering the content from simple to complex (Van Merrienboer & Sweller, 2005), or breaking the content into parts (Kester et al., 2010) are strategies used to prevent overloading the working memory and to manage intrinsic load. Extraneous load emerges when the instruction's materials or guidelines are not designed appropiately for learning (See Van Merrienboer & Sweller, 2005; Pouw et al., 2019). Spreading knowledge over time or space (Kalyuga et al., 1998; van Merrienboer ve Sweller, 2005; Pouw, Rop, De Koning ve Paas, 2019), giving place to unnecessary information in the learning material (Kalyuga et al., 1998; Van Merrienboer & Sweller, 2005; Pouw et al., 2019), and resorting to random techniques such as trial and error to solve a problem can cause an increase in extraneous cognitive load. Integrating the related written information into a geometric figure (Kalyuga et al., 1998), avoiding unnecessary information (Kalyuga et al., 1998), and presenting a particular part or all of the solution steps of the problem (Paas et al., 2003; Van Merrienboer & Sweller, 2005) are used to reduce the extraneous cognitive load. Germane load occurs during the construction of new schemes and getting automaticity in existing schemes (See Paas et al., 2003). The german load in the working memory must increase to ensure learning. Asking students to make self-explanations about the learning material (Kalyuga, 2011) and imagine how they can solve a given problem (Leahy & Sweller, 2004) causes the germane load. The total amount of these three loads must not exceed the working memory capacity for learning. Managing the intrinsic load, reducing the extraneous load, and increasing the germane load enable optimum use of the capacity of the working memory (Van Merrienboer & Sweller, 2010; Khalil & Elkhider, 2016). In this study, "the effect of an instruction, designed by taking CLT as a reference frame and executed in DGLE, to develop the mental rotation skills of pre-service mathematics teachers" was investigated. In this scope, the research questions below sought answers.

- What is the effect of the instruction, designed by taking CLT as a reference frame and executed in a DGLE, to improve the mental rotation performance of pre-service mathematics teachers?
- What is the effect of the instruction to improve the mental imagery skills of pre-service mathematics teachers?
- What is the effect of the instruction on developing the mathematics language use of the pre-service teachers?
- What is the effect of the instruction on developing the concept schemas of pre-service mathematics teachers about rotation and its component?

Method

This section is explained in seven subheadings: (a) research group, (b) participants, (c) data collection and procedures, (d) teaching sessions, (e) validity and reliability, (f) data analysis, and (g) credibility and ethics.

Research Design

In this study, an individual teaching experiment (Steffe & Thompson, 2000) was used to examine the effect of an instruction, designed based on CLT and executed in a dynamic geometry learning environment (DGLE), on the development of pre-service mathematics teachers' mental rotation skills. The teaching experiment includes a series of successive teaching sessions (Cobb & Steffe, 1983) that are recorded by technological tools (e.g., video camera, sound recorder) (Steffe & Thompson, 2000). The teaching is carried out with a single student or several students, a teacher, and an observer who witnessed the sessions (Steffe & Thompson, 2000). A sequence of hypotheses, generated before the teaching sessions, are tested during the sessions (Steffe & Thompson, 2000). The researcher can change some of these hypotheses and produce new ones, considering the collected data from the learning environment and the findings obtained from the tested hypotheses.

The teaching experiment was conducted in three steps for the study: pre-evaluation—teaching sessions— post-evaluation. To investigate the mental rotation skills of participants, in the pre-and post- evaluations, they were asked to answer to a multiple-choice test and a research instrument and were made interviews with them. After the pre-evaluation, the four teaching sessions were held with each participant to develop the participants' mental rotation skills.

Participants

A purposeful sampling technique (See Creswell, 2013; Palys, 2008) was used to determine the participants of this study. This technique requires considering a set of situations compassing the study sample, the teaching place, and teaching style (Palys, 2008). It provides a selection of the most suitable participants who can give detailed and in-depth information about the studied subject (Mertens, 2020; Sargeant, 2012). The study sample was selected in second-year pre-service mathematics teachers of the Primary School Mathematics Teacher Education Program at a state university. The criteria for participation in this study were such that performing below the basic level in PSVT (Guay, 1976) of 36 questions, underperforming in the MRATs of 10 tasks, being able to express their thoughts and views in the interviews effectively, and being a volunteer for participating in teaching sessions.

Selecting the sample by some predetermined criteria is one of the strategies (criterion sampling) used in the purposeful sampling technique (See Patton, 1990; Mertens, 2020). The researchers set up some criteria and then selected the sample among those who met those criteria (Mertens, 2020). This sampling strategy allows identifying the most suitable sample that may provide information-rich situations to reveal major system weaknesses that may be contributed to the improvement of a program or system (Patton, 1990). To determine who should have been in the attendances of the instruction it was asked all pre-service teachers to respond Purdue Spatial Visualization Test (PSVT) and the Mental Rotation Assessment Tasks (MRATs). However, only females among the responders of both met these criteria, and the four among them formed the study sample. Many studies investigating the connection between the gender factor and spatial ability drew attention that males outperform females on spatial ability tasks (See Reilly et al., 2017; Yuan et al., 2019).

Data Collection and Procedures

Two types of data, quantitative and qualitative data, were collected within the scope of this study. The Rotation Questions of PSVT (12 multiple choice questions) and the Mental Rotation Assessment Tasks (10 tasks that required to answer through writing) were asked to participants before and after the instruction to collect quantitative and qualitative data. These data collection tools were mentioned as pre-PSVT Rotation Questions (pre-PSVT: RQs), post-PSVT Rotation Questions (post- PSVT: RQs), pre- Mental Rotation Assessment Tasks (pre-MRATs), post- Mental Rotation Assessment Tasks (post-MRATs) throughout this paper. pre/post-PSVT: RQs and pre/post-MRATs supplied quantitative information about participants' mental rotation performances. Qualitative data were obtained from the pre/post-MRATs and interviews that were made based on these tasks.

In pre/post-PSVT: RQs, an object and its image after the rotation(s) were presented to the participants, and then they were asked to select the image to be obtained among the options when they apply the same rotation(s) to another object. pre/post-MRATs were prepared from the first researcher of this paper by taking an expert's opinion. pre/post-MRATs, designed based on CLT, were in two categories. Single-axis rotation tasks (6 tasks) of low cognitive load were in the first category, and two-axis rotation tasks (4 tasks) of high cognitive load were in the second category. Participants' written responses to pre/post-PSVT: RQs and pre/post-MRATs enable quantitatively evaluation of their mental rotation performances.

In the task-based interviews, participants were asked to express how they answered pre/post-MRATs to interpret, understand and unravel their mental imagery skills while performing these tasks. Then, participants were asked questions regarding the concept of rotation (and its components) to gather information about their concept schemes. These probe questions were as following. Can you explain what the term rotation means for you? What is the direction of rotation? What is the angle of rotation? The interviews ensured to evaluate participants' concept schemas about the rotation as well as mental imagery skills. In addition, the participants' written responses to pre/post-MRATs supplied qualitative information on their mathematical language uses.

Teaching Sessions (Instruction)

CLT was taken as the reference frame to design the teaching sessions executed in a dynamic geometry learning environment (DGLE). The instruction’s focus was to develop participants' mental rotation skills containing mental rotation task performance, mathematical language use, mental imagery skills, and concept schemes about the rotation and its components. Instructional content, activities, and materials are designed to manage their intrinsic loads, reduce their extraneous load, and increase their germane loads. Thus, their working memory loads were tried to be kept in balance. The participants' answers to pre-MRATs guided designing the teaching sessions. Each participant attended four teaching sessions, each of which lasted about 90 minutes and was recorded.

Managing intrinsic load: The complexity of the rotation tasks in each session and throughout the sessions was increased gradually. The first two sessions included single-axis rotation tasks (first category tasks), while the last two sessions included two-axis rotation tasks (second category tasks) (See Table 1). The tasks in each teaching session were divided into sub-tasks, which were resembled utilized in the same or the previous session(s). In this way, two-axis rotation tasks were performed based on one-rotation tasks.

Table 1.

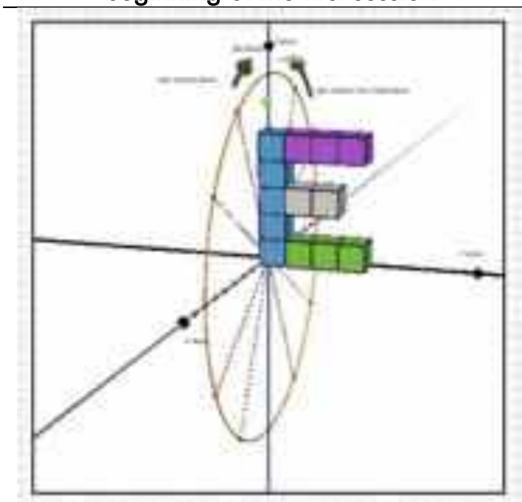
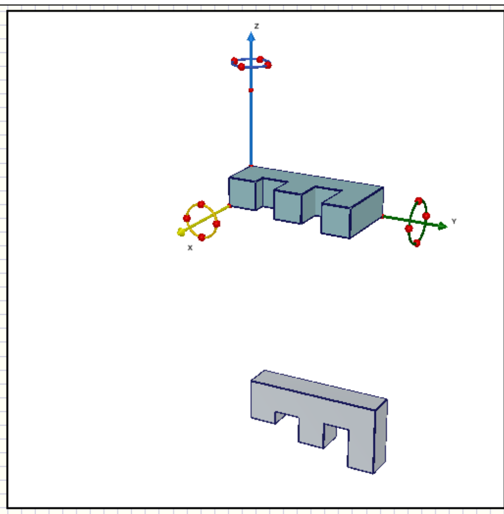
Tasks Included in Each of the Teaching Sessions

Session	Tasks used in each teaching sessions
First session	Rotating a solid around the given single axis by a specific direction and angle. Identifying the single axis rotational motion from the given solid and its image.
Second session	Identifying the single axis rotation from the given solid and its image, and then rotating another solid according to this identified rotational motion.
Third session	Rotating a solid around the given two axes by specific directions and angles. Identifying the two-axis rotation from the given solid and its image.
Fourth session	Identifying the two-axis rotation from the given solid and its image, and then rotating another solid according to this identified rotational motion.

Reducing extraneous load: Category-specific Cabri3D materials were designed for each session. Participants were able to practice the rotational motions that they imagined concerning the tasks using those materials. They checked in Cabri3D whether they correctly defined the rotation axis, direction, and angle. They also checked whether they appropriately made the image of the rotated object in their minds. The Cabri3D materials in the first teaching sessions drew the participants' attention to the rotation and its components. The rotation axis was made thicker and painted in a different color in the Cabri3D materials. The rotation directions were highlighted and given labels. Similarly, the rotation angle was distinguishable by the participants. When the instructor understood that participants internalized the rotation and its components, s/he used different Cabri 3D materials in which these components of the rotation were indistinguishable.

Figure 1.

Cabri 3D Materials Designed for the First Teaching Session

Sample Cabri 3D material used in the beginning of the first session	Sample Cabri 3D material used in the last of the first session
	

Increasing the germane load: The variability effect was created by changing the rotated solid, the rotation axis, direction, and angle measure while retaining the task category-specific properties. In each teaching session, participants tried to solve these tasks produced through the variability effect. Thus, they had an opportunity to construct schemes to solve category-specific tasks. Participants were encouraged to imagine each task's solution process and make self-explanations regarding their solutions. They were given such types of guidelines. Imagine how the solid appears after rotated 90 degrees clockwise around the x-axis. Explain what changes were happened to its appearance.

Validity and Reliability

Different tools can be utilized to collect research data (Zohrabi, 2013), for example, tests, assessment tools, surveys, or interview questions. The validity of these tools depends on "whether they are evaluating what is supposed to evaluate" (Zohrabi, 2013, p.258). The properties of these tools are important for the research because the study results are reached from the information obtained through them (Burns, 1999; Zohrabi, 2013). According to Zohrabi (2013), the research tools can be reviewed by experts for validity. Pre/post-PSVT: RQs, pre/post-MRATs, the task-based interview questions, and the tasks in teaching sessions were the data collection tools of this study. PSVT is a measurement tool that confirms the validity used to assess the spatial abilities of individuals over the age of 13. The Pre/Post-MRATs, the interview questions and tasks in the teaching sessions reached their final forms by getting an expert opinion. Providing reliability of the data and findings, the researcher can involve two or more experts in the analysis, interpretation, and validation of conclusions (Nunan, 1999). By considering Nunan's expressions, the data and findings obtained from this study were analyzed separately by two experts. The inconsistencies in the analyzes were examined and evaluated until reaching an agreement.

Data Analysis

The quantitative and qualitative content analyses (Hashemnezhad, 2015) were used to analyze the collected data. The quantitative content analysis was used for the data coming from the written assessment tasks and PSVT. It provided to report communication content systematically, objectively, and numerically (Berelson, 1952). The qualitative content analysis was used for the data coming from the interviews. It helped to classify and summarize the verbal and behavioral data (Hancock, 1998). Quantitative and qualitative analysis were carried out in this study as follows. *Analyzing the quantitative data:* It was counted how many of the pre- and post-PSVT: RQs and the pre/post MRATs were answered correctly by each participant. The numbers found were converted to ratios or percentages and were compared. *Analyzing the qualitative data*: It was grouped the difficulties of the participants before the instruction into three themes. (1) Inadequate mental imagery skills to visualize the rotation(s) process in mind, (2) inability to use mathematical language to describe the rotational motion(s), and (3) insufficient concept schemes regarding the rotation and its components (rotation axis, direction, and angle).

After the instruction, whether the participants still had the same difficulties in pre-determined themes were examined. Shortly, whether participants' mental rotation skills developed were analyzed.

Credibility and Ethics

Ethics involve requirements on necessity of the study, the protection of identity and rights of the participants and the publication of the information collected from the study (Fouka & Mantzorou, 2011). This study was launched after the necessary permissions were obtained from the relevant department of the university. The written consent was taken from each pre-service teacher who participated in each stage of this study. Taking consent from the participants for their participation is one of the researcher's obligations (Parveen & Showkat, 2017). Participants were also informed that if they dedicided to discontinue the study, they could leave at any time of it. Participants were mentioned with pseudonyms to protect their identities throughout this paper. Researchers have an obligation to take care of the participants' confidentially and personal information or identity (Parveen & Showkat, 2017).

There are various credibility techniques in the literature. "Credibility is defined as a faithful description of the phenomenon of interest" (Liao, 2015, p.47). For the credibility of the study, "any argument inferred from data should be strong and convincing, and any claims or statements made should be logical and based on well-grounded premises" (Kvale, 1996, as cited in Liao, 2015, p. 48). Peer debriefing, one of the credibility techniques, requires involving professionals in analytic discussions and data interpretations (Lincoln & Guba, 1985) who have prior experience on the research topic (Johnson & Christensen, 2012). Peer debriefing was applied in this study. Having experience with the research topic and knowing how to research is carried out, traced, and reviewed each stage of the study, the expert controlled the data collection and analysis processes, and made comments, evaluations, criticisms, and judgments.

Findings

In this section, findings were presented regarding the effect of the instruction, designed by taking CLT as the reference frame and executed in DGLE, on pre-service mathematics teachers' mental rotation skills development. The findings were handled in the three subsections: participants' mental rotation skills before the instruction, the instruction process, and their rotation skills after the instruction. The focuses of these sub-sections were: (1) participants' mental rotation performances, (2) mental imagery skills, (3) mathematics language use, and (4) concept schemes.

Participants' Mental Rotation Skills Before the Instruction

The number of participants' correct answers and their percentages in the pre-PSVT: RQ is presented in Table 2. Each of them correctly made less than 60% of these questions. The performances of Tugce and Ozge were under the basic level, while the performances of Melis and Pınar were at the basic level.

Table 2.

The Number and Percentage of Correctly Answered pre-PSVT: RQs

pre-PSVT: RQ	Performances	Tugce	Melis	Pınar	Ozge
Before	Number of correct answers	4	7	7	5
	Percentage of correct answers	%33	%58	%58	%41

The correct response rates of the participants in the pre-MRATs were presented in Table 3. Ozge answered all the questions incorrectly. The other participants gave correct answers at most two of the tasks. However, the tasks answered correctly by the participants belong to the first category. Any of them could not answer the tasks in the second category correctly.

Table 3.

Correct Response Rates of Participants in the First and Second Category Tasks of pre-MRATs

pre-MRATs	Categories/ Participants	Tugce	Melis	Pınar	Ozge
Before	First category tasks (6 task)	2/6	2/6	1/6	0/6
	Second category tasks (4 task)	0/4	0/4	0/4	0/4

The task-based interviews after the pre-assessment demonstrated that participants could not perform the tasks correctly because they had misconceptions about rotation and its components. Although participants did not experience much difficulty imagining rotations in the first category tasks, they had difficulty imagining rotations in the second category tasks. One of the first category pre-assessment tasks was in Figure 2. Participants were asked to express how to object on the left side was rotated to obtain the image on the right side. Was the object is rotated about which axis, in which direction, and at what angle? When the object given on the left side is rotated 90 degrees clockwise about the y-axis, its image given on the right side is obtained. Transcripts taken from the interviews, made with Ozge, revealed that she could imagine the object's movement even though she could not mathematically express this rotation.

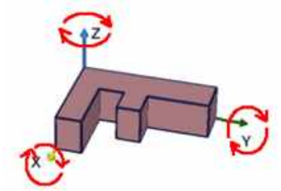
> Researcher: How did you rotate the object? Can you describe it?
> Ozge: I lifted this shape up at 90 degrees by holding from this axis ... I held it from this Z-axis. I turned it backward. Those arms of this shape became in an upright position. I seated this shape on its invisible back-side face.

Figure 2.

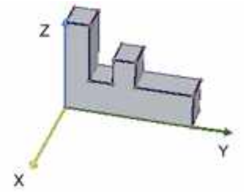
One of the First Category Tasks in pre-MRATs

A Single-axis Rotation Task
In below, the image on the right is obtained by applying a rotational movement to the object on the left side. Write in the dotted areas about which axis, in which direction, and at what angle the object was rotated.

Before



After



Axis of the rotation: ....
Direction of the rotation: ....
Angle of the rotation: ....

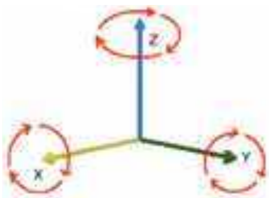
One of the second category pre-assessment tasks was in Figure 3. It contains E shaped object, its image after the rotations, and the chair-like object. First, participants were asked to express the movement of the E-shaped object mathematically, i.e., its rotation axis, direction, and angle. Then, they were asked to apply the same rotation to another chair-like object and describe the change in the appearance of the chair-like shape and its new image after the rotations. In interviews, it was detected that participants experienced difficulty both imagine the rotations and explain these rotations mathematically. They also could not rotate the chair-shaped object as the E-shaped object. From the interview section, it can be seen that Melis could not imagine how the E-shaped object was rotated, so she could not apply the same rotations to the chair-like object.

> Melis: I don't know how to repond this task... I do not know how to think... I'm confused... I can't think.

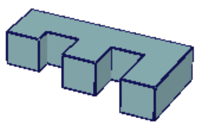
Figure 3.

One of the Second Category Tasks in pre-MRATs

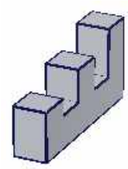
A Two-axes Rotation Task
In below, an object on the left side and its image on the right side after two-axis rotation are given in the first line. How was the object on the left rotated to obtain the image on the right? Write the appropriate mathematical expressions in the dotted areas. If the same rotational movements are applied to the object on the left side in the second line, describe the image which will form after the rotations.



Before



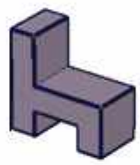
After



First rotational movement
Axis of the rotation: ....
Direction of the rotation: ....
Angle of the rotation: ....

Second rotational movement
Axis of the rotation: ....
Direction of the rotation: ....
Angle of the rotation: ....

Before



After

Rotation is a circular movement of an object about an axis or a point. The study indicated that the participants could not understand the rotation of an object when actualized around a specific axis. They could not deduce how the rotations are actualized by establishing connections between the solid and its image. They could not comprehend that the rotation actualized around one of the orthogonal axes, in a specific direction (clockwise or counterclockwise) and at an angle with a particular number of degrees. They thought they could move the object by applying a force, such as dropping, pushing, or lifting. They did not think that the object moved by rotation.

> Researcher: How was this image obtained by rotating this object?
>
> Melis: How was this shape obtained?... I thought that the object upright was beaten down backward, so the object laid on its back face...

Participants resembled the origin of the 3D coordinate system, its axes, and the object located on the coordinate system to a fulcrum, lifting arms and bulk, respectively. They believed that they could rotate an object by holding and moving those axes. They tried to move the object from right to left, from back to front, and from bottom to top through the axes. In addition, the axis and the direction of rotation were not two different concepts for them. Transcripts taken from the interviews of Melis and Ozge revealed that they had misconceptions about the axis and direction of rotation.

> Melis: I think that the axis of rotation and the direction of rotation are almost the same. The axis of rotation indicates in which direction we rotate the object.
>
> Ozge: We always hold the object from one of these axes and move it. I used the z-axis to lift up an object. I used the x-axis to turn the object from left to right and used the y-axis to turn the object from right to left.

Participants stated the directions of rotation independently of the axes, although they should have determined the direction of the rotation (clockwise and counterclockwise) relative to the given axes. They used contextual direction expressions. For example, I turned the object from inside to outside or from outside to inside. I turned the object from front to back or from back to front. They did not take the rotation axis as the reference point to determine the rotation directions. The interview section taken from Melis's speech was given as an example of this situation.

> Melis: The direction of rotation indicates where an object will turn. It indicates whether this object will rotate towards this side or that side. For example, if I rotate this object (she held an eraser with her hand) like this, it will turn towards the front. If I rotate it like this, it will turn towards the back.

Generally, participants were correctly able to state the measure of the angle of rotation in first-category tasks. However, they did not use the terms of the axis and/or direction of rotation correctly while specifying the rotation angle. This situation means that they did not conceptualize the rotation angle or did not have an adequate concept schema about it. The transcript taken from the interview with Tugce revealed that she did not have adequate concept knowledge about the angle of rotation, so she thought that she could move the axes to rotate the objects at a particular degree. The images obtained from rotating an object 90 degrees clockwise and 90 degrees counterclockwise around a specific axis are different.

> Tugce: I thought of the rotation angle as making the objects have an inclination. I rotate the objects using the axes. I can rotate an object by tilting the axes. If I tilt the axis, I can give an angle to the object.

The Instruction Process

In the first teaching sessions' activities (the example screenshots from the sessions were in Figure 4) participants performed single-axis rotation tasks. The instruction started with tasks requiring participants to rotate a solid about the x-axis and followed through with the y-axis rotation tasks and z-axis rotation tasks, respectively. Meanwhile, the instructor helped participants use Cabri3D materials in a meaningful way so that s/he tried to remove their misconceptions about the rotation and its components. For this, s/he drew their attention to the properties of Cabri3D materials: the thicknes of the axis, the labels of axes, the arrows and labels of the direction of rotation, and the circle segments given to determine the angle measures; and guided them to focus on these properties while using Cabri3D materials. The instructor also began by asking the participants guiding questions in the first session to get them thinking about the properties of rotational motion and its components, and continued to ask guiding questions in the next instructional sessions that allowed them to discover its more critical properties: "Did the axes move when the body rotated? What is the distance of this point on the given solid from the rotation axis before (after) the rotation?" When the instructor realized that the students were beginning to distinguish how to rotate the body about each axis of rotation, each direction of rotation, and each angle of rotation without confusing these concepts, he had them work with Cabri 3D materials with the clues, such as the thickness of the axis of rotation and the directional arrows, removed. However, if the participants experienced challenges distinguishing the rotation axis or the direction of rotation, they were allowed to re-examine the starting Cabri3D materials. Such activities supported the development of concept schemas of the participants concerning the rotation and its components. The interview section taken from the first session gives information about how the instruction was executed to develop the conceptual knowledge of participants.

The interview section taken from the first teaching session made with Ozge:
Researcher: Can you describe the image that will obtain when you rotate this solid 90 degrees clockwise around the x-axis?
Ozge: Is this what you named with the x-axis? I don't understand how the solid is rotated around the x-axis. I couldn't do similar tasks in the exam.
Researcher: Examine the material presented in Cabri3D. For example, what is written on the thick axis? What is written on the others?
Ozge: The x-axis. That's the y axis, and the other one is the z-axis.
Researcher: Yes.
Ozge: What are you mean when you were saying clockwise?
Researcher: In Cabri, the clockwise and counterclockwise directions in connection with the x-axis are also labeled with arrows. You can see if you examine.
Ozge: Then, the clockwise is this direction... But I still don't understand how to rotate the solid around the x-axis.
Researcher: Can you grip the yellow button with the mouse and turn it in the direction labeled as clockwise?
Ozge: (the solid rotates) Isn't that the rotation about the z-axis? When the x-axis is mentioned, aren't we holding the x-axis and turning it like this?
Researcher: Did the axes move when you rotated the solid?... What changes have occurred?
Ozge: No. It's not what I imagined. It's not like I thought…

Figure 4.

The Screenshots Taken from the First Teaching Sessions

The first two of four teaching sessions included single-axis rotation tasks, while the remaining sessions included two axes rotation tasks. The complexity level of the tasks increased within a session and over the consecutive sessions gradually. In this way, they learned to deal with diverse tasks by starting from the simple ones and advancing through to complex ones. In addition, practising with many tasks made it possible for the participants to acquire the needed skills to perform the tasks.

Throughout the instruction, participants tried to imagine the rotational movements and the appearance of the solids after rotations and to explain the static or dynamic image in their minds using mathematical language and checked whether they performed the tasks correctly through Cabri3D materials. At the same time, the instructor followed such approaches: giving directions to the participants to perform the tasks by decomposing them into sub-tasks; evaluating the responses of the participants and providing immediate feedback regarding those responses; making the participants use Cabri3D both for checking whether their answers were correct and supporting their mental image formation processes (especially when they were unable to perform the tasks). In addition, s/he encouraged the participants to explain how they performed the tasks in detail by referring to mathematical terms and guided them to correct their deficiencies and mistakes in using mathematical language. For example, if a participant forgot to mention one of the rotation's components while describing how she performed the task, the instructor warned her to complement their missing information. Through the Cabri3D materials and the instructor's guidelines, if a participant could not imagine a rotation or the rotated solid at the beginning of a session, she started to have less imagination skill on the following tasks the same session. Similarly, with the instructor's encouragement, participants paid more attention to whether they used correct mathematical terms and utilized more mathematics terms when explaining how they did tasks. The interview sections provide information about the carried-out instruction process to improve the participants' skills of mental imagination and mathematics language use.

> *The interview section taken from the first teaching session made with Tugce:*
> Researcher: Rotate the solid in Cabri3D. Does the same image emerge as you described?
> Tugce: I'm rotating it about the y-axis... No, it's not the same. Look, there is a cube on this rectangular prism. I thought this cube was seen on the left side of this prism. But I recognized that I was wrong because that cube is on its right side.
> *The interview section taken from the third teaching session made with Pınar:*
> Researcher: First, can you rotate the solid 90 degrees counterclockwise about the z-axis, and then can you rotate the image, that will obtain after the rotation, in your mind, 90 degrees clockwise about the y-axis.
> Ozge: What did you say? I must take a note first...around the z-axis, this is the z-axis, I must rotate it like this (waiting for three or four minutes) ... the right side becomes the front side... wait a minute...I can not imagine... It's like my mind has stopped.
> Researcher: You can apply to Cabri3D if you can not imagine if you experience a challenge
> Ozge: (She is rotating the object in Cabri3D).
> Researcher: What kind of change occurred in the image of the object? Can you describe it now?
> Ozge: Yes. The left face of the solid became its front face. Its lower riht edge, previously on the x-axis, intersected with the y-axis after the rotational movement…
> *The interview section taken from the fourth teaching session made with Merve:*
> Researcher: Here is given a solid and its image obtained after it was rotated about two axes. Can you mathematically state the rotational movements in an order?

Merve: Methinks, fisrtly, it was rotated to 90 degrees about the y-axis.
Researcher: In which direction?
Merve: Please wait a minute, it was rotated in the clockwise... it was not...in the counterclockwise .... yes, firstly, it was rotated to 90 degrees counterclockwise about the y-axis.
Researcher: If you rotate the given solid as you just said, can you describe the image to be obtained?
Merve: (She described)
Researcher: Can you explain the second rotational movement mathematically.
Merve: If I rotate it once again...namely, I will rotate the image that is what I just mentioned... I rotate it 180 degrees clockwise around the z-axis, I can obtain that image (she is pointing out the image in Cabri 3D)
Researcher: Can you apply the rotational movements that you said onto the Cabri3D in order? Thus, you can check your guesses whether they are correct.

Participants' Mental Rotation Skills After the Instruction

The number and percentage of correct answers of participants for pre/post PSVT Rotation Questions were in Table 4. Participants' PSVT performances increased after the instruction (See Table 4). Tugce, Melis, and Pınar performed above the basic level in the post-PSVT: RQs, while Ozge performed at the basic level in it. Ozge's performance was affected less by the instruction compared to the other participants.

Table 4.

The Number and Percentage of Correctly Answered pre-PSVT: RQs and post-PSVT: RQs

PSVT: RQ	Performance	Tugce	Melis	Pınar	Ozge
Before	Number of correct answers	4	7	7	5
	Percentage of correct answers	%33	%58	%58	%41
After	Number of correct answers	10	11	10	7
	Percentage of correct answers	%83	%91	%83	%58

The correct response rates of the participants in the pre/post-MRATs were in Table 5. Tugce and Pınar correctly answered all the instructions tasks (See Table 5). Tugce, Pınar, and Ozge correctly answered all the tasks in the first category of post-MRATs while Melis made a mistake in one of these tasks. Tugce, Melis, and Pınar correctly answered all tasks in the second category of the post-MRATs, but Ozge made mistakes in two of these tasks.

Table 5.

Correct Response Rates of Participants in the First and Second Category Tasks of pre-MRATs and post-MRATs

Categories/Participants		Tugce	Melis	Pınar	Ozge
First category tasks (6 tasks)	Before the instruction (6 tasks)	2/6	2/6	1/6	0/6
	After the instruction (6 tasks)	6/6	5/6	6/6	6/6
Second category tasks (4 tasks)	Before the instruction (4 tasks)	0/4	0/4	0/4	0/6
	After the instruction (4 tasks)	4/4	4/4	4/4	2/4

The task-based interviews based on the post-MRATs showed that the participants conceptualized the rotation and its components. After the instruction, participants did not experience difficulty mentally rotating the object and retaining its image in their memory. They deduced the rotational movements from the object and its rotated image. They found the appropriate mathematical expressions describing the rotations. They understood how to rotate the object from the given mathematical explanations. The participants, except Ozge, mentally imagined the rotational movements in each of the second category tasks and applied these rotations to another object. One of the tasks of the first category of the post-MRATs was in Figure 5. The task includes a T-shaped object and its image after the rotation. Then, participants should have mathematically explained the rotational movement applied to the object. The transcripts taken from the interview made with Ozge show that she could mentally imagine the rotational movement applied to the object and explain it mathematically.

Ozge: Now, what had been done to this object, and this image was obtained... This was rotated 90 degrees counterclockwise about the z-axis.

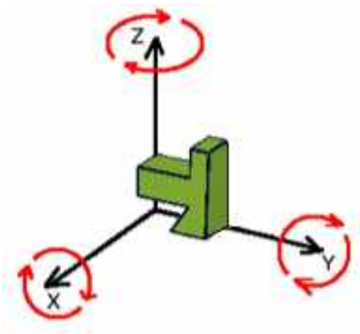
Figure 5.

One of the First Category Tasks in post-MRATs

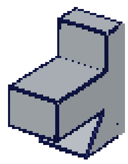
A Single-axis Rotation Task

In the following, the image on the right is created by rotating the object on the left. Write in the dotted areas about which axis, in which direction and at which angle the object was rotated.

Before



After



Axis of the rotation: ………………….
Direction of the rotation: …………………..
Angle of the rotation: ……………………

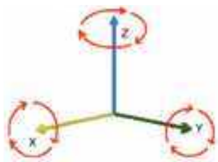
One of the second category tasks of post-assessment was in Figure 6. It contained a chair-like object, its image after the rotations, and the F-shaped object. Participants should have explained mathematically the rotational movements applied to the chair-like object. Then, they should have described the image obtained after applying these rotations to the F-shaped object.

Figure 6.

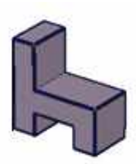
One of the Second Category Tasks in post-MRATs

A Two-axes Rotation Task

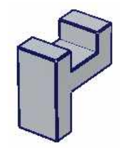
In below, an object on the left side and its image on the right side after two-axis rotation are given in the first line. How was the object on the left rotated to obtain the image on the right? Write the appropriate mathematical expressions in the dotted areas. If the same rotational movements are applied to the object on the left side in the second line, describe the image which will form after the rotations.



Before



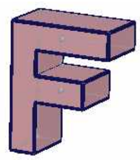
After



First rotational movement
Axis of the rotation: ....
Direction of the rotation: ....
Angle of the rotation: ....

Second rotational movement
Axis of the rotation: ....
Direction of the rotation: ....
Angle of the rotation: ....

Before



After

Participants, except Ozge, did not experience difficulty imagining the rotations and applying them to the F-shaped object. Transcripts taken from the interview with Melis revealed that she could mentally imagine the rotational movements applied to the chair-like object. She used the appropriate mathematical expressions to describe these movements. She could also accurately describe the image obtained after applying the same rotations to the F-shaped object.

> Melis: It was rotated 180 degrees counterclockwise or 180 degrees clockwise around the x-axis. Both ways are correct. If I rotate this like in the above, 180 degrees clockwise about the x-axis, the object will sit on its upper face. The top face will be the bottom face, and the bottom face will be the top face. The top face will lie along the negative side of the y-axis, and these two arms will point out the left side. Again, if I rotate it 90 degrees clockwise around the z-axis, the top face will be the bottom face, and the bottom face will be the top face. Namely, it will be the same as after the first rotation movement. When I compare the new image with its initial form of the object, the left face will be the front face, and the right face will be the back face. Those arms of F will look to the back.

If a distance of any point taken on the object from the axis before the rotation is "r" units, this distance will not change while this point rotates around this axis. The situation is the same for all points on the object. Even though participants initially had misconceptions about the rotation at the begging of the instruction, they learned the properties of the rotation concept during the sessions. The sections, taken from the interviews made with Tugce and Melis, exemplify this situation.

Melis: Let this be the axis of rotation (he held a pencil in his left hand). And let this be the object (she held an eraser in her right hand). If there is a distance of 2 cm between the object and the axis, the object will not move away from the axis while rotating it, and the distance will remain the same.

Tugce: Keeping the distance constant. Keeping the distance between the axis and the object during the rotational movement and keeping the distance constant, while rotating the object around an axis with an angle of a specific degree.

During the instruction, they understood that the 3D coordinate system presented in the tasks does not move, its axes are stable, and only the objects are rotated around these axes. Although some tasks had not got a coordinate system and axes labels, they could explain the rotational movements using mathematical terms. They conceptualized the axis of rotation as a line passing through the center of the circles drawn by each point of a rotating object. From an object and its rotated image, they could deduce the rotation axis by completing the arc between the object and its image to a circle. Tugce's explanations revealed that she learned what the rotation axis is and could determine where the location of the rotation axis was.

Researcher: What is the rotation axis?
Tugce: It is the axis around which I rotate an object.
Researcher: What does that mean?
Tugce: Where do I actualize the rotation? Am I actualizing it around x? Am I actualizing it around y? or am I actualizing it around z? Namely, which is the reference axis of the rotational movement?
Researcher: For example, in this task, how did you find out that the object was rotated about the x-axis?
Tugce: I understood it from here. For instance, I don't know the axis where I'm rotating this object around. When I rotate the object, only the inner line remains fixed. This axis is the x-axis. We can think of it as a reference line. When I rotate all the points on the object, this line remains fixed, so the x-axis is the only non-rotating thing. From here, I understood that I am moving around the x-axis.

Participants stopped using the expressions of the direction of rotation relative to their own context. They learned to determine the clockwise and counterclockwise directions by referencing the arrow of the positive direction of each axis on the 3D coordinate system. The transcript below indicates that Melis learned how to determine the direction of rotation.

Melis: Let that pencil be the z-axis. Let that point be the positive end of the z-axis. This positive end of the pencil point at me. I determine the direction of rotation according to how I look at this positive end. Then I can express a circular motion from left to right in the z-axis as the clockwise rotation relative to my viewpoint. The direction from right to left will be counterclockwise.

The position of a point on the object before the rotation, the orthogonal projection of this point on the rotation axis, and the position of this point after the rotation form the rotation angle. An angle measure without a direction may not accurately characterize the rotation angle. Both the measure and the direction are needed to picture an angle. In the instruction, participants recognized that rotating an object clockwise and counterclockwise about a given axis produces different images. They realized how to form a rotation angle. In addition, they discovered that the image of an object after it was rotated 'n' degrees clockwise around a specific axis and the image of the object after it was rotated '360-n' degrees counterclockwise around this axis are the same. The transcript taken from the interviews made with Tugce is an example of these situations.

> Researcher: What is the angle of rotation?
> Tugce: It is the angle that the object makes with the axis while rotating.
> Researcher: Can you give me an example?
> Tugce: Let me give an example. This is the axis of rotation, and this is our object (she took a pencil to represent the axis and an eraser to represent the object). I want to carry this object to this position (she rotated the object at 90 degrees counterclockwise around the axis). To bring this object to this position, I need to rotate the object around this axis.
> Researcher: For example, if you rotate it 30 degrees?
> Tugce: Different situations may arise when we say 30 degrees rotation angle. When I'm rotating this object, I do not consider only its angle measure. The angle of rotation also has a direction. The measure of the angle is not enough for the rotation. The direction is also required. For example, if I rotate it 30 degrees clockwise, I will rotate the object downward. But if I rotate it 30 degrees counterclockwise, I will rotate it upward. So two different situations arise.

Discussion, Conclusion, and Suggestions

The results of this study show that instruction designed based on CLT and delivered in DGLE improved the mental rotation skills of pre-service teachers. This finding is consistent with other studies in the literature on spatial skills and cognition. A lot of studies revealed that DGLEs and computer-assisted learning environments help students to develop their spatial abilities (See Güven & Kosa, 2008; Kurtulus & Uygan, 2010), as well as their mental rotation skills (See Samsudin et al., 2011; Ozcakır-Sumen, 2018). In addition, some studies (See Woolf et al., 2003; Rodenburg et al., 2018) reported that the computer-based learning environments designed according to students' cognitive levels and adapting the educational tasks relative to their cognitive needs maximize educational efficiency.

The term mental imagery refers to "visualising (Gavilan & Avello, 2020)," seeing in the mind's eye (Kosslyn et al., 2010)," "retrieving an object, situation, or event from memory," "reliving a version of the original stimulus or a novel combination of stimuli (Pearson et al., 2015, p.590)" and the "generation, review, maintenance, and transformation of mental images to accomplish a task (Guarnera et al., 2019) ". Mental rotation tasks require mental imagery (See Guarnera et al., 2019). In mental rotation tasks, a mental image of a 3D object or a stimulus related to the rotational movements is created from immediate perceptual visual information or previously stored information from long-term memory (See Guarnera et al., 2019). Working memory is responsible for maintaining the image of the object in mind, inspecting its properties, rotating this image of the object, and maintaining the image obtained after the rotation(s). The study revealed that the instruction, carried out by considering the cognitive loads of the participants and executed in DGLE, developed their mental imagery skills. Before the teaching sessions, they had difficulty understanding the rotational movements from the given object and its image after two-axis rotation. After the sessions, they usually imagined the rotational movements applied to the object. They were also able to apply these rotations to another object. Shortly, they could perform more complex tasks, such as the two-axis rotation tasks requiring strong mental imagery skills. This finding is compatible with other studies (Lambert, 2011; Epler-Ruths et al., 2020). According to Lambert (2011), computer graphics provide a bridge between an individual's mental imagination and the external reality and facilitate his/her mental imagination through their virtual space (Lambert, 2011). Dynamic visualizations help reduce students' cognitive load by making abstract concepts more concrete and by depicting complex objects, situations, or events that are difficult to imagine so that students can easily recognize the patterns in visual data and draw correct inferences (Epler-Ruths et al., 2020).

The language of mathematics includes terms and symbols that must be defined unambiguously, different from the natural language (Ilany & Margolin, 2010). A term in mathematics language can be used in natural language with a different meaning than its meaning in mathematics language (Ilany & Margolin, 2010). Students, incapable of using the language of mathematics, may perceive and interpret this mathematical term depending on the context where it is used and may assign a different meaning to it (Ilany & Margolin, 2010). This study showed that participants did not know the terms related to the rotational movement before the instruction. They tried to explain the rotations by using the words found in their natural language, such as lifting an object up, holding the axis, and turning the object from front to back. However, the instruction helped them develop their skills in using mathematical language develop their mathematical language. Thus, they could express the rotational movements in the tasks by using correct mathematical terms during and after the teaching sessions. This finding is consistent with what Jones (2001) pointed out in his study. "The use of dynamic geometry software can assist students in making progress towards the more mathematical explanation" (Jones, 2001, p.50).

Students enter university with misconceptions about different subjects (Verkade et al., 2017). Identifying and correcting them is important because they can hinder learning more complex concepts (Verkade et al., 2017). This study showed that pre-service mathematics teachers had misconceptions about the rotational movement, so they could not perform the mental rotation tasks correctly. The instruction enabled pre-service teachers to develop concept schemas regarding the concept of rotation and its components. They did not make errors caused by misconceptions about rotation and its components in the post-assessment. This finding is parallel to the findings of other studies in mathematics and science. According to the studies on correlation, probability, decimals, and diffusion and osmosis, simulation-based learning environments help students reduce their misconceptions by helping them interact with real-world processes or systems and enabling them to see the impact of their own decisions (Liu, 2010; Gurbuz & Birgin, 2012; Huang et al., 2008; Meir et al., 2005; Verkade et al., 2017).

Unlike many studies in the field, this study allowed examining the development of mental rotation skills of participants in terms of four dimensions: performance, concept schema, mental imagination skill, and mathematical language use. One-to-one interactions during the interviews and the instruction allowed the instructor, who was also one of the researchers of this study, to simultaneously detect the changes in participants' spatial and mathematical thinking ways. However, the individualized instruction may have been affected by the needs or progresses of the study participants. Furthermore, preferring the individual data collection approach for most of the research led the study to be conducted with a limited number of participants, four female pre-service mathematics teachers. For this reason, it is unknown whether the study findings can be generalized on a larger sample size of both males and females, such as a classroom, or whether they can be generalized to a sample of younger individuals, such as high school students is unknown. Given that, whether the instruction designed within the scope of the study will improve the mental rotation skills of different sample groups may be investigated.

This study provides a promising perspective on how DGLEs can be integrated into the instruction that targets to develop pre-service teachers' mental rotation skills through utilizing CLT as a design framework. This perspective draws attention to specific points that should be considered for the instructional design, associated with the organization of the content, the materials to be used, and the learning activities. These were: The necessity of sequencing the tasks from the simple to complex, the benefits of decomposing the task into subtasks, the importance of designing Cabri 3D materials parallel to the sequenced tasks utilized along with the instruction, the advantage of integrating mathematical language into Cabri3D materials through self explanations and the provided opportunity for unification the mental imagination with Cabri 3D materials. These approaches that shape the instructional design of the study are known to be used to manage, reduce and increase the load of working memory. In this study, the effectiveness of each instructional approach on the learning process or cognitive load of each of the participants could not analyze. Therefore, it is recommended to design and carry out research that reveals how changes occur in the mental rotation skills of learners or their cognitive loads (i.e., amounts in connection with the cognitive load types) relative to the applied instructional approaches.

Although the literature points to the effects of DGLEs on the development of individuals' mental rotation skills, this is not sufficient to answer how effective and efficient instruction should be designed. However, CLT offers a promising perspective on how DGLE should be integrated into instruction. Considering the individual's cognitive architecture when designing DGLEs allows learners to engage in tasks that match their abilities during the learning process. Such instruction is one of the most effective and efficient ways to develop individuals' mental rotation skills.

Ethics Committee Approval: This study was produced from the first author's doctoral thesis, called "Investigate the development of spatial skills in the dynamic geometry environment of middle school mathematics teachers candidates", published in 2018. Although the protocols set by Anadolu University Ethics Review Committee (ERC) was followed throughout the study, an ethics committee approval was not available for this study, because the approval of the Faculty of Education Dean's Office was sufficient for the reasearchs before 2020.

Informed Consent: Informed consents were taken from the participants before the research.

Peer-review: Externally peer-reviewed.

Authors' Contributions: Concept— H.B.Y.; Design— F.K.; Supervision— H.B.Y., Data Collection and Processing—F.K.; Analysis and Interpretation— F.K., H.B.Y; Literature Review— F.K., Writing— F.K.; Critical Review- All authors.

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Appendix

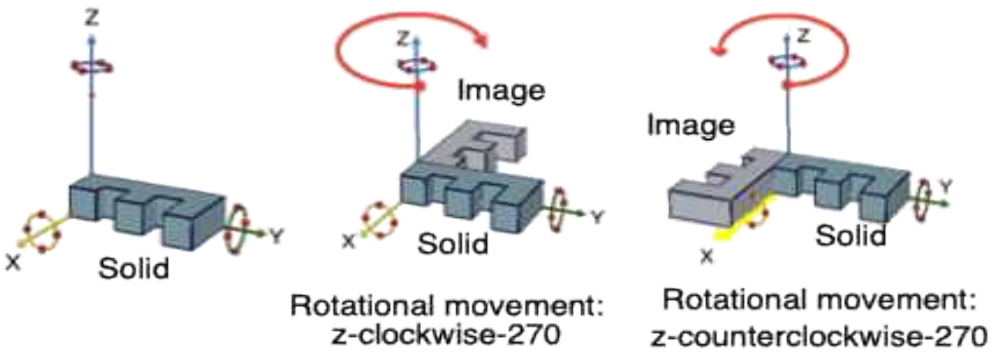
A

Example Interview Questions Taken from Pre- and Post- MRATs:

What is rotation? Can you explain to me?
When you hear the term "axis of rotation", what comes in your mind? Can you explain to me?
What is "direction of rotation"? What do you know about that term? When you heard that term what comes in your mind? Can you explain to me?
What is "angle of rotation"? What do you know about that term? When you heard that term what comes in your mind? Can you explain to me?

B

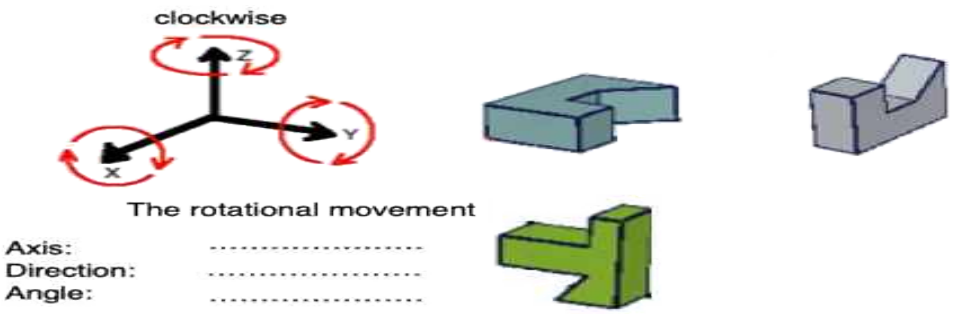
Example rotational movements represented through a Cabri 3D material during the instruction:



C

Example single-axis rotation task taken from Pre- or Post- MRATs:

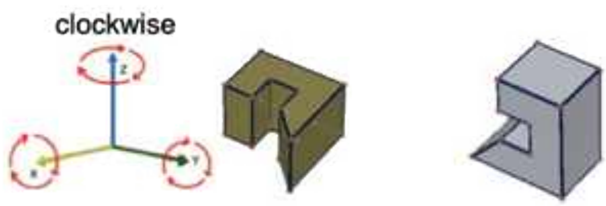
If you apply one rotational movement (single-axis rotation) to the solid on the upper left, you can obtain the image given on the upper right. Apply the same rotational movement to the second solid on the lower left, and explain the image to be obtained on the lower right detailly. Besides, state the rotational movement mathematically (rotation axis, direction of rotation, and rotation angle), and write your answer on the dotted parts of the paper.



D

Example two-axis rotations task taken from Pre- or Post- MRATs:

If you apply two rotational movements (two-axis rotations) on the solid on the left, you can obtain the image given on the right. State the rotational movements mathematically (rotation axis, direction of rotation, and rotation angle). Write your answer on the dotted parts of the paper. Give reasons for your answer.



The first rotational movement		The second rotational movement	
Axis:	....	Axis:	....
Direction:	....	Direction:	....
Angle:	....	Angle:	....