TurtleGO: Application with Cubes for Children's Spatial Ability Based on AR Technology

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Abstract. In this paper, we introduce a new application called TurtleGO that uses augmented reality (AR) technology, with which K-2 children can experience a geometric sense of the egocentric perspective. This application was developed with the concept of Logo-MicroWorlds, which allows children to examine and simulate their geometric ideas in a virtual world with a turtle agent. TurtleGO provides children with real-time feedback in a monitor representing the augmented turtle image on blocks based on AR technology while children are playing with actual blocks. Our application is flexible and inexpensive as it makes possible the use of various sized cubes already in possession. All the children between grades 2 through 5 improved in their ability to distinguish pair of stimuli as identical or mirror images when they used TurtleGO. However, we found that our application provides an effective and intuitive AR learning environment to lower grade elementary students, improving their spatial transformation skills since upper graders could solve the tasks easily without it.

Keywords: Augmented reality (AR) · Tangible interaction · Body syntonic · Spatial ability · Egocentric perspective · Spatial transformation

1 Introduction

The Common Core State Standards for Mathematics (CCSSM) suggests that children from kindergarten to grade 2 should learn to identify, describe, analyze, compare, and reason various shapes and the attributes of those shapes in geometry [1]. Also, it is recommended that students take lessons to create, draw or analyze two- and three-dimensional shapes in order to learn about the characteristics of the shapes and describe the relative positions of these objects using terms such as 'above, 'below', 'beside', 'in front of', 'behind' and 'next to' in later grades. Therefore, it becomes necessary to provide a variety of opportunities for students to experience their geometric senses with not only "flat" shapes but also "solid" objects.

Spatial ability defined as a fundamental cognitive ability that includes retrieving, retaining, and manipulating visuo-spatial information [2, 3] is an important factor in the Science, Technology, Engineering, and Mathematics (STEM) fields including

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geometry [4, 5]. Although there had been prejudice that spatial ability was fixed, Uttal [6] concluded that it can be improved through training because of its malleability. Activities with manipulative materials such as blocks, puzzles, shape games [7, 8] or utilization of relational language regarding space [9] would improve spatial abilities of children including preschoolers.

Among the several spatial abilities, spatial transformation is classified into object-based transformation, which is the imaginary movement of an object on an axis, and egocentric perspective transformation, which is the imaginary movement of one's perspective in relation to other objects [10]. From the view of an egocentric perspective, students can describe other objects around them using terms such as "front," "back," "left," and "right" [11].

Papert [12], who have developed constructionism, believed children could learn the concept of geometry by using "body syntonic." He claimed that children think of the turtle's motion by imagining themselves as the turtle, moving under two commands—rotate and forward—in the virtual world. As these two commands have already been embodied in humans, Papert suggested children could gain geometric sense easily when they simulate, explore, and develop their thoughts in the logo-MicroWorld with 2D figures by using these commands. In other words, even if children cannot study geometry through rigorous definition, they can learn it through tools that are appropriate for their level.

We propose a new application "TurtleGO," based on Augmented Reality (AR) technology and expect that it would be a helpful tool for children to learn and experience the sense of the spatial transformation. They would acquire a strategy of the view of the egocentric perspective transformation through the application, regarding the augmented turtle agent as themselves. Also, they would be able to express the movement of the turtle using "body syntonic" for recognizing three dimensional objects.

2 Related Work

Radu [13] conducted a meta-analysis of 26 studies about augmented reality in education. The research identified positive effects of AR based learning compared to non-AR based learning in regard to enhanced understanding of spatial structure contents or language associations, long-term memory retention, and student motivation. Also, the disadvantages of AR based learning were described as a difficulty in use, an ineffective integration in classroom, and displaying little to no effect depending on the person or contents. The author suggested in the conclusion that AR based learning may be utilized as an effective tool for teaching 3D spatial but may not be effective for text or 2D content.

In education, AR technology were used with tangible objects such as cards, cubes or blocks, and has provided the opportunity to acquire abstract knowledge including programming and mathematics for children. [14]. Zhu et al. [15] introduced an educational game based on AR technology teaching abstract concepts such as color mixing, mathematics, and two- and three- dimensional shape recognition for preschool children. It allowed children to use physical cards and blocks to construct buildings in the virtual world. Jin [16] developed a tangible programming tool named AR-Maze, which consisted of games on mobile devices, location map and three kinds of programming blocks to connect the game. Children were provided with an intuitive and exciting environment paired with audio, textual or image feedbacks when they were coding. However, most of the research used their own tangible materials to connect physical to digital devices. This made them expensive to use or hard to get. They were used many times for a specific-purpose rather than for a general-purpose. Therefore, we have made our application utilizing cubes of various sizes available for everyone's use.

Bujak et al. [17] established a framework of three perspectives, including physical, cognitive, and contextual perspectives in order to understand the AR use in mathematics classroom. First, through physical manipulations, younger students become easily involved in educational content and they could interact naturally with objects. In other words, their cognitive load which is not directly related to learning goals since the physical object has an affordance the children already know. Second, in the case of cognitive dimension, children have to learn abstract concepts in mathematics, thus information aligned spatiotemporal properly used by AR can assist student's symbolic understanding by scaffolding, or connecting the physical and the abstract. Third, on the contextual perspective, AR experience could make children construct personally meaningful experience of learning as it lets them easily access the virtual world, contextually relevant content and engage with personally-relevant content.

From the perspective of Bujak et al., our application TurtleGO has educational benefits in three dimensions: physical, cognitive and contextual. Since our application TurtleGO is used based on the children's block activity, it could be said that the affordance of the object, that is, the play with blocks, causes a natural interaction in the physical dimension. In the case of cognitive dimension, it displays the augmented turtle on the block where the children put it down, so it is possible to identify the movement of the turtle directly. Children can explore a three-dimensional object by considering themselves as moving the turtle, which reduces their cognitive load by properly placing information. Finally, in contextual dimension, children can have their own meaningful experiences as they can manipulate the blocks in their own way.

3 TurtleGO

3.1 Design Inspiration

Turtle Geometry and JavaMAL MicroWorld. In the perspective of Constructionism coined by Seymour Papert, learning is most effective when learners experience an activity by constructing meaningful knowledge [18]. Therefore, Papert proposed that geometry could be educated to elementary students by using a turtle metaphor, a "tool for thought," in the Logo MicroWorld, which can construct figures by two commands —forward and rotate—movements children already embodied.

According to this idea, Cho et al. [19] suggested a 3D representation system—JavaMAL—by which learners can write executable expressions to generate 3D polycubes in the Web 2.0 environment. For instance, if the learner imagines the path of the imaginary turtle and writes down an executable expression “s” into JavaMAL MicroWorld, then a unit cube would be added to the previous form as the imaginary turtle is moving one step forward from the previous position. Thus, to create their favored shape, learners only have to imagine the turtle’s path where it goes forward or rotates and write down executable expressions: “s” (to go forward), “r” (to go right), “l” (to go left), “u” (to go upward), “d” (to go downward), “R” (to turn right), and “L” (to turn left) (Fig. 1). Since the cubes were made according to the executable expression students write down, it could trace student’s thinking process as they use JavaMAL MicroWorld. Being involved in the activity would construct and deepen the mathematical knowledge for users through the process of generating, constructing, sharing patterns, and producing outcomes using the cubes in the JavaMAL MicroWorld [19–22].

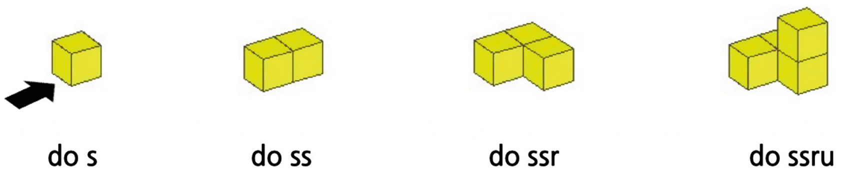


Fig. 1. Example of polycube formations and executable expressions. The arrow indicates the direction of the imaginary turtle.

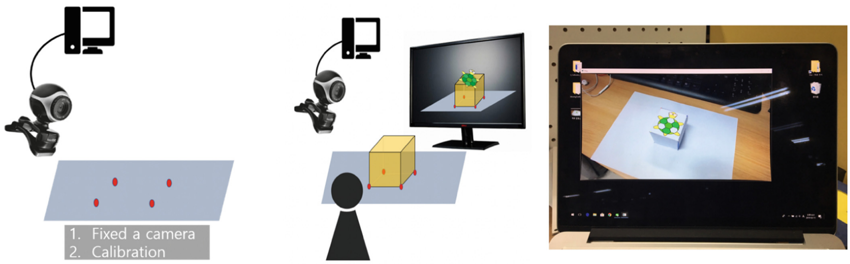
Unfortunately, this activity is not suitable for younger children since their cognitions are not developed enough to understand the concepts. Therefore, we wanted to provide an environment for younger children with tangible cubes and show the augmented turtle rather than flat objects on the monitor or the turtle children had to imagine. We expected that they could imagine a turtle’s path without a turtle after experiencing a hands-on activity with real cubes with our TurtleGO.

3.2 TurtleGO

TurtleGO using augmented reality (AR) technology needs a camera and a monitor to provide students with an experience of a tangible interaction. It allows the student to see the virtual turtle in real-time feedback. While they play with tangible cubes, children can see the turtle on a cube in the monitor, as shown in Fig. 2(b). Children can recognize the movement of the turtle, which depends on the placement of cubes. They are expected to distinguish mirror images of the turtle’s path they imagine in 3D stimuli.

As TurtleGO is a user-friendly system, teachers may find it easy to use. This becomes an important issue as the turtle is controlled by teachers while the children are playing with the blocks. Therefore, teachers should be able to easily teach their children according to their intentions by determining the turtle’s direction at the starting point.

TurtleGO is both economical and flexible in that this application does not require further purchase of tools and equipment but can be run in the classroom with no difficulty. During the activity using the application, children were able to reach the desired level of understanding and performance, which includes designing a turtle's path in 3D shapes to recognize three-dimensional objects or distinguish mirror images.



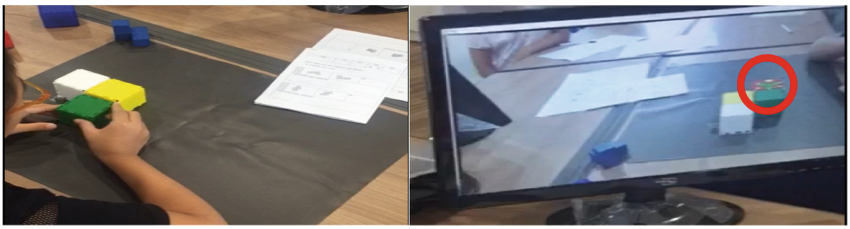
(a) preparation (b) playing

Fig. 2. TurtleGO overview

Our application displays an augmented object on a cube through the monitor, which requires two steps. First, the camera has to be fixed so that the camera can picture the whole scene of the hands-on activity. Second, to visualize the turtle on a cube, the four vertices of the position of the initial block's bottom face has to be input into the program for calibration as shown in Fig. 2(a). Then, the teacher moves the augmented turtle using letters on the keyboard: "w" (to go straight), "a" (to go left), "s" (to go back), "d" (to go right), "u" (to go up), and "j" (to go down); the teacher can also change the direction of an augmented turtle with the "e" key, based on cube arrangement.

4 Pilot Study

In order to find the most effective grade for using TurtleGO, we conducted a pilot test on volunteers from second to fifth grade and compared the results of a group who were engaged in TurtleGO with the group who were not (Fig. 3(a) and (b)).



a) A child playing with blocks. b) Children could recognize where the turtle moves from.

Fig. 3. Pilot study

4.1 The Tasks

Although TurtleGO used by ‘body syntonic’ might be available to improve geometric sense or spatial ability, we chose the spatial transformation tasks by providing mirror images in Soma cube easily accessible to the children (Fig. 4). This strategy will aid with imaging the turtle’s path and analyzing turtle’s perspective to identify if children will think the tasks are too difficult to perform.

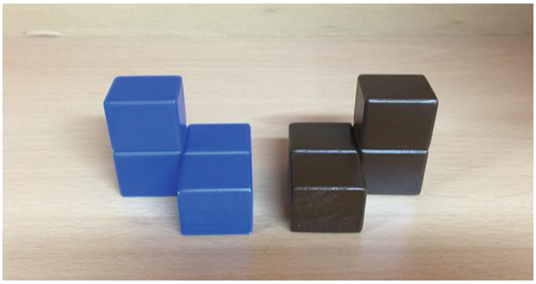


Fig. 4. Mirror images in Soma cube

To confirm that they had the ability to imagine and analyze the path of the turtle, the children were asked to take another test called perspective-taking test, testing for whether they could identify the left or right of an agent—the turtle—before the tasks.

4.2 Procedures

We divided the students into two groups—one with TurtleGO hands-on activity included in the session, the other without the activity. As the control group, 19 children (12 girls and 7 boys from grade 2 to 5 and aged 9 to 12, (M = 10.05, SD = 1.08)), were asked to take a paper-and-pencil test. After being provided with an explanation about mirror images and the turtle geometry, they took another paper-and-pencil test on spatial transformation consisting of pieces in the SOMA cube (Fig. 5). A week later, the other group of 14 children (8 girls and 6 boys from grade 2 to 4 and aged 9 to 11, (M = 9.64, SD = 0.63)), went through the same process with the control group. However, students in this group were instructed to participate in the block-building activity and shaped pieces in the SOMA cube with TurtleGO before taking the same paper-and-pencil test. Both sessions took about 30 min.

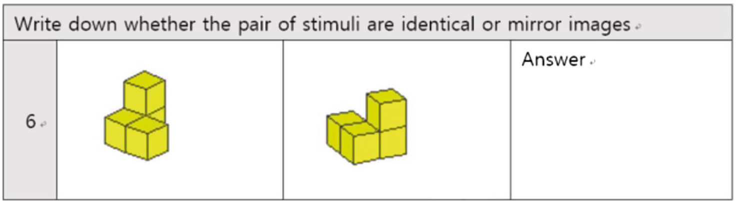


Fig. 5. Example of the spatial transformation task

We asked the children to mark and write the path they imagined the augmented turtle would take on the test sheet expecting that they could distinguish the stimuli based on the virtual turtle's path they have written down.

4.3 Results

We compared the results of spatial transformation tasks between the control group and the experimental group. Although the number of children who participated in the session of the control group was 19 and that in the experimental group was 14, we analyzed only 13 children's answers (3 in grade 2, 4 in grade 3, 3 in grade 4, 3 in grade 5) in the control group and 11 children's answers (3 in grade 2, 6 in grade 3, 2 in grade 4) in the experimental group since the others did not take the test seriously or had already learned a mental rotation skill. Children could take part in only one session, but we made three children (3 in grade 3) participate in both sessions to compare the paired data according to the use of TurtleGO. Our findings have three aspects.

First, in general, the children in the experimental group could better distinguish whether the stimulus was identical or mirror images. Even though all children were asked to distinguish the mirror image and to justify their answers, some children in the control group answered "they are the same" for all the questions of the test or the others replied "I don't know." When requested why they thought it was the same, they answered "it looks the same" or "they are the same if one stimulus would rotate." Even though it was not the same. On the other hand, the children of the experimental group imagined the path of the turtle agent and provided a rationale for themselves whether they thought the two stimuli were the same or different from each other.

Second, only one of the three participants who participated in both sessions performed worse after using TurtleGO. He scored 10 out of 10 questions first, but only 9 out of 10 same questions after using TurtleGO. When imagining the path of the turtle, he was somewhat confused to decide whether the stimuli were the same, one of which was rotated in the z-axis. As all children in both groups could not distinguish the pair of the stimuli rotated in the z-axis, this gives us a clue that TurtleGO might not be useful when the stimulus is rotated in the z-axis.

Third, although we found tendency supporting the fact that higher the grade, the better performance in the experimental group, it was confirmed that it would be used more meaningfully as an educational tool for second graders since upper graders can solve the tasks easily without TurtleGO.

5 Case Study

Through the pilot test, we wanted to verify whether the lessons using TurtleGO in the classroom could provide effective help to the grade 2 students in solving spatial transformation tasks. We tested with a group of second graders in a classroom setting with the same tasks of the pilot study except for an item rotated in the z-axis. In Korea, every classroom of elementary school is equipped with a TV screen and a computer to show audiovisual materials for students. To conduct a case study, we used the TV screen and physical cubes, which were already in the classroom. We also used cameras and laptops because of the installation issues of the application. If teachers wanted to use our application, they could install it on their computer.

5.1 Procedures

Three lessons were held for 40 min at a time during the span of two weeks with 27 students (13 boys, 14 girls), a researcher and a teacher. The teacher confirmed that there were no problems in contents and operations before the experiment.

In the first lesson, children were presented with an explanation of mirror images and the rotation tasks and they took a perspective-taking test as same as the pilot test. After the end of the first lesson, TurtleGO was introduced.

In the second lesson, after given a brief review of the first lesson, students observed the two stimuli by touching pieces of SOMA cube. The paper-and-pencil test on spatial transformation tasks was performed. Although the strategy of egocentric perspectives was introduced, no strategies for solving the tasks were suggested. The test was the same as the one used in the pilot test, but the item with a z-axis transformation task was removed.

In the final lesson, seven children had the opportunity to manipulate the cube with our application and all students could see the augmented turtle on the large display in front of the classroom (Fig. 6). The teacher could explain the path of the augmented turtle and change the direction of it as needed, and the students shouted together the path of the virtual turtle watching the display. The same test on spatial transformation tasks was conducted at the end of the lesson after experiencing TurtleGO. The whole lesson was video recorded.

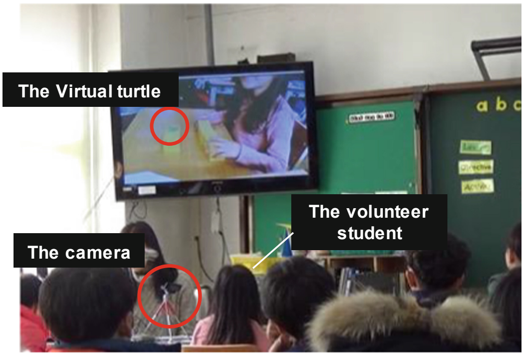


Fig. 6. A screenshot of recorded video from the case study

5.2 Results

As in the study of Radu [13], the children were highly motivated when the lesson was given with TutleGO based on AR technology and actively volunteered for a role in manipulating the cube. They were in a situation where they were learning, but they seemed to be experiencing play rather than study.

We analyzed the perspective-taking test, pre- and post-tests on spatial transformation tasks of 27 students with 1 point per item. The perspective-taking test had 16 items and the test on spatial transformation tasks had 9 items. First, the result of the perspective-taking test presented that 7 children (Group A) were found to have difficulty in distinguishing between the left and the right side of the agent. Their average score was only 5.33 out of 16 while the average score of the others (Group B) was 14.8 and the median score was 15 (Table 1).

Table 1. Comparison between Group A and Group B.

	Group A	Group B
The number of children	7	20
The average score	5.33	14.8

The data of pre- and post-test on spatial transformation tasks was classified with four groups. The first group was 8 students who performed better after using TurtleGO. The second group was 6 students who maintained high scores in both pre- and post-test on spatial transformation with little difference in performance. The third group was 11 students who received low scores both before and after the use of TurtleGO. The fourth group consisted of 2 students who performed lower after using TurtleGO. The average scores for each group can be seen in Fig. 7 and the distribution of two groups classified by the results of the perspective-taking test in each group categorized by the results of the spatial transformation tasks is presented in Fig. 8.

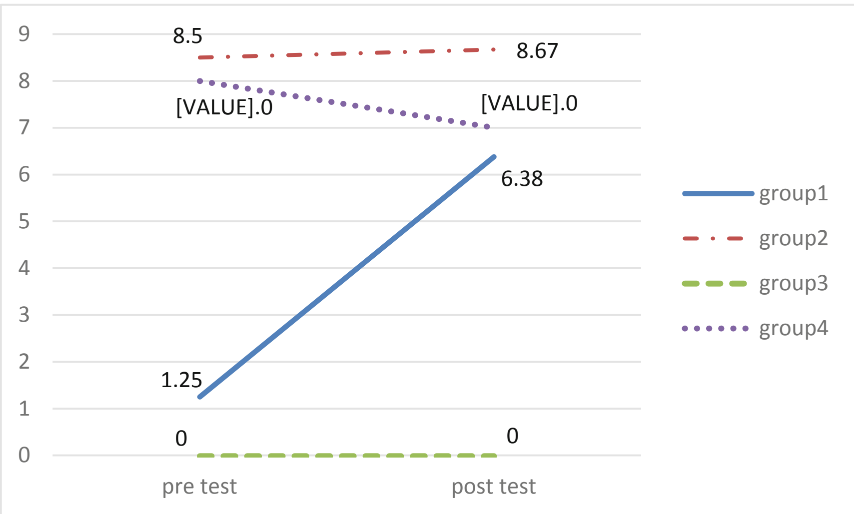


Fig. 7. The average scores of the pre- and post-tests on spatial transformation tasks in categorized groups

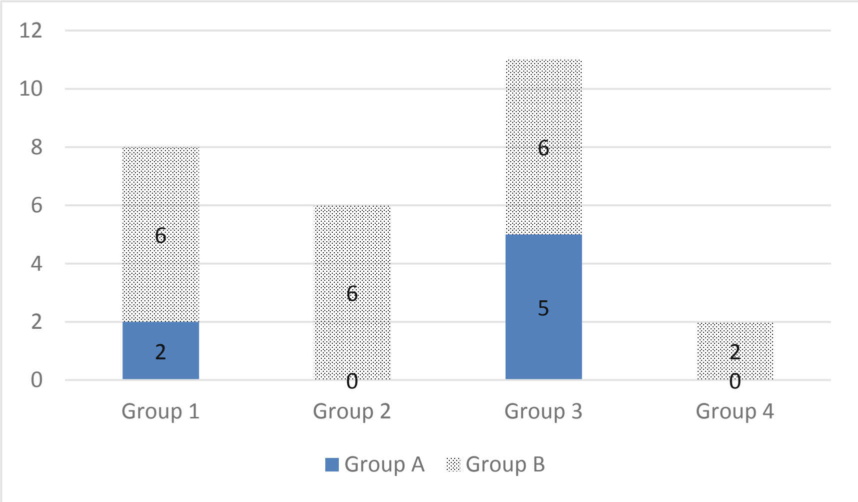


Fig. 8. The distribution of the two groups classified into the lower (Group A) and upper (Group B) groups of the perspective-taking test in categorized groups

We concluded TurtleGO was an effective tool for group 1 while it was a useless tool for group 3 as they showed no improvement. Group 2 presented little improvement from the average score but they had already gotten a high score. Contrary to our expectation, group 4 showed a drop in the score after using TurtleGO while they were good at the perspective-taking test.

The results of group 1's pre-and post-test scores can be seen in Table 2. The scores of the students in group 1 were dramatically enhanced after hands-on activity with our application. The majority of them received a zero score in the pre-test, but their post-test score increased by as little as 4 and as much as 7. Participant 7 and Participant 8 was in group A which meant they had a poor skill for perspective-taking test. We could assume that not only skills for spatial-transformation tasks but skills of perspective-taking were improved through using TurtleGO.

Table 2. Pre- and post-test scores of students in group 1

	P1	P2	P3	P4	P5	P6	P7	P8
Pre-test	0	0	0	0	6	0	0	4
Post-test	6	7	4	5	9	6	5	9

In the case of group 4, the detailed results of their scores are presented in Table 3. Although two students in group 4 got 8 points in the pre-test they lost one score after using our application. When determining whether the stimuli were identical or mirror images they used the strategy of the mental rotation in the pre-test rather than the strategy of imaging virtual turtle's path used in the post-test. And both of them was in group A of perspective-taking test.

Table 3. Pre and post-test scores of students in group 4

	P9	P10
Pre-test	8	8
Post-test	7	7

6 Discussion and Conclusion

In a constructionist's opinion, students can construct abstract knowledge from concrete experience. Therefore, TurtleGO gives children a chance to experience and identify identical or mirror images using a virtual turtle so that they may improve spatial transformations skills, and thus, spatial ability. We confirmed that TurtleGO led elementary students to learn intuitive and empirical strategies of spatial transformation and to distinguish whether the stimuli are identical or mirror images when using blocks. This visually oriented application might allow students to understand the perspective-taking skills as well.

There are some limitations that exist in this application. In order to start using the application, teachers are required to input four points of the bottom of the initial block, and this process may become tricky. Therefore, we suggest to utilize our application with AR markers to overcome this difficulty by finding the exact coordinates of the first cube. Using AR marker can further simplify the preparation phase. Second, teaching with TurtleGO was not beneficial to everyone. As shown in the Freitas and Campos [23] study, AR-based learning was useful for students with low or average achievements but not for high-performing students on spatial transformation tasks. For students with high achievement, we suggest further research that show the effectiveness after adjusting the difficulty of task performance.

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