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GeoSolvAR Coding Scheme for Spatial Perspective-Taking: Augmented Reality and Gesture-Enabled Learning in Special Education

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Abstract: This paper introduces GeoSolvAR, an adaptive interactive learning environment based on an augmented reality (AR) and gesture-based interaction paradigm that supports the development of the ability called spatial perspective-taking – the capacity for an individual to imagine the world from the viewpoint of someone other than herself. To support this ability, GeoSolvAR provides a series of 3D interactive high-immersive visualizations accompanied by intuitive gesture-driven interactions. We evaluated GeoSolvAR using an adaptive-tutoring randomized controlled trial with 60 children with special educational needs (SEN) between the ages of 8 and 14. The GeoSolvAR learning metaphor was compared with its two-dimensional counterpart previously employed for instructional purposes. Spatial perspective-taking is traditionally difficult to master, yet we observed a 35% increase in task performance and a 40% reduction in completion time. Qualitative data also highlights increased engagement and motivation levels in the GeoSolvAR group.

Keywords— Augmented Reality; Gesture-Based Interaction; Spatial Perspective-Taking; Special Education; GeoSolvAR; Coding Scheme; Spatial Cognition; Educational Technology

1. Introduction

Consider spatial perspective-taking, for instance: it's the ability to sequence the relationship between objects and movement, to mentally rotate things and grasp how they'd appear from another viewpoint. These skills are vital for most everyday tasks, as well as learning subjects such as geometry, engineering, and geography. So, when special-needs kids struggle with cognitive processing, their spatial abilities often lag as well, making it hard for them to progress in school or navigate the world[1]. Their teachers can encounter similar difficulties, but traditional teaching methods of static slideshows and abstract lectures tend not to work for these learners[2]. There's a growing need for educational tools that respond to the specific learning needs of special educational needs (SEN) students[3].

Augmented Reality (AR) is another powerful new tool for education because it combines real-world experiences with digital information in a seamless and immersive way[4]. In AR, users can interact with virtual objects that appear in the real world in real-time. Learning platforms like MERGE Cubes which combine AR with gesture recognition allow students to touch and manipulate virtual objects using their natural hand gestures[5]. AR and gesture-based learning tools offer a multimodal way of learning that has significantly benefited children with special needs. Students can learn about abstract spatial concepts by engaging in multimodal activities that directly involve their hands. Gesture-based learning can be more intuitive for students, making it a natural and efficient way to engage with learning materials. [6] [7].Although AR holds promise for general education learning, there are few studies to explore its application in special education and, more specifically, for developing spatial perspective-taking[8]. Research studies conducted so far have shown the effectiveness of AR for students in learning geometric and spatial concepts. However, they are limited in demonstrating the additional benefits of gesture-based interactions in AR for children with special needs[9].To address this gap, the GeoSolvAR coding scheme introduced here integrates 3D AR with gesture-enabled learning that focuses on the development of spatial perspective-taking for special needs children. By adopting a more immersive and interactive learning paradigm where students actively engage with 3D geometric objects that they can manipulate in real-time with intuitive hand gestures, the adoption of gesture-enabled learning in 3D AR holds the potential to provide a more engaging learning experience for children with special needs.The study examines the extent to which the GeoSolvAR system can be used to improve spatial perspective-taking abilities among children with special needs – by carrying out a randomized controlled trial with 60 children aged between 8 and 14 years. The performance of the students using the GeoSolvAR system is compared with that of students working on the same content using traditional learning tools – by using various measures, such as task performance, task completion time, and their levels of engagement, to see how the combination of AR and gesture-based interaction influences their spatial cognition.[10] It is hoped that the success of the GeoSolvAR system in improving the spatial reasoning abilities of children with special needs helps to extend the literature on the use of AR and gesture-enabled learning for special education.

2.Materials and Methods

2.1 GeoSolvAR System Design

GeolvAR system was created using the 3D game-engine Unity3D and the Vuforia SDK, which serves as a comprehensive augmented reality development platform. The GeoSolvAR system also utilises the Leap Motion SDK, which is used for gesture recognition. We use the Leap Motion device to allow users to rotate, translate and scale 3D objects in the scene using natural hand gestures. The system tracks hand gestures in real-time, and translates them into manipulations of the 3D objects, while conforming to the following equation:

$$f(x,y,z,\theta)=R(\theta)\cdot v(x,y,z)\ldots(1)$$

where R(θ) represents the rotation matrix, and v(x,y,z) is the position vector of the object. It allows the learner to practice looking at geometric figures from different perspectives. It is a flexible and versatile design. Multiple levels of difficulty are available and appropriate to individual learners, delivered in real time with visual and aural feedback to guide learners through the task.

2.2 Spatial Perspective-Taking Tasks

Participants practised a series of visuospatial perspective-taking tasks, in which they used their right hand to manipulate 3D objects (eg, cubes, pyramids and polyhedra) in virtual space, so that it matched a given target orientation. This included having to take on egocentric perspectives, rotating the virtual objects upside down and backwards, as well as allocentric perspectives, looking from other virtual points of view. The system can record the rotation accuracy for each practised perspective-taking task by using its real-time feedback mechanism in the following way:

$$E=\sum_{n}^{i=1}|\theta_i-\theta_{target}|\ldots(2)$$

where θi is the participant's object orientation and $\theta target$ is the correct orientation. Tasks were designed to scale, growing more complex as participants mastered what they already knew and offering more immediate feedback through adjustments in real time. The gestural interaction, where people literally shaped the air with their hands, rendered the abstract spatial analogies more concrete and thus easier to grasp.

2.3 Demographics and Group Assignment

We recruited 60 children aged 8 to 14 years, with different types of special needs. The participants included children diagnosed with Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD), learning disabilities and mild cognitive impairments. Children were recruited from local special education schools. We specifically chose children with difficulties in spatial reasoning and cognitive development to ensure that this Recipe for Biology task would be particularly difficult.The children were randomly allocated to one of two groups, either the group who received learning on the GeoSolvAR app (the experimental group), or the group who received traditional learning through physical boards (the controls), with 30 in each group. This was done to ensure that the groups were similar at baseline, in terms of cognitive abilities and diagnoses, and that the only variable they would differ on was the type of learning. Parental consent was obtained, and the study had ethical approval before starting.

2.4 Experimental Design

For this purpose, we conducted a randomised controlled trial to compare GeoSolvAR with the conventional learning methods of spatial awareness improvement. Participants were randomly divided into two groups: a GeoSolvAR group and a control group (N = 30 for each). The GeoSolvAR group used the AR-based system with gesture-based interactions to explore geometry, while the control group learnt geometry with conventional spatial learning methods, such as manipulating 3D physical models and reading geometric diagrams printed out on paper. We compared the change of participants' performance through gave both the GeoSolvAR group and the control group the pre-test and the post-test. The pre-test and the post-test both consisted of four sections

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with increasing difficulty. We calculated the change of performance through the following equation:

$$\Delta P = \frac{Spost - Spre}{T} \ldots..(3)$$

where ΔP represents the performance improvement, Spre and Spost are the pre- and post-test scores, and T is the time taken to complete the task. This formula accounts for both accuracy and task completion efficiency in evaluating the participants' spatial reasoning skills.

2.5 Data Collection and Analysis

The quantitative data from these form part of the data we collected by performing pre- and post-tests on spatial reasoning performance and task completion times. We then used a paired t-test to assess whether there was a significant improvement between GeoSolvAR and the control group. Last, we used ANOVA to assess whether there were significant differences between children with different diagnoses (for example, between children with ASD and children with ADHD). The following figure shows an example of our engagement metric, which quantifies time spent by each participant interacting with the system:

$$E(t) = \int_{t1}^{t2} I(t)dt \ldots.(4)$$

where E(t) represents the engagement level, and I(t) measures interaction intensity over time. Qualitative data were collected from interviews with educators and participants, and thematic analysis was applied to understand usability and satisfaction.

3.RESULTS

3.1 Task Performance

As the results demonstrate, there is a significant improvement in the task performance for the GeoSolvAR group over the control group, and this holds for a range of tasks that require spatial reasoning and perspective-taking. We observe that the improvement rate for the GeoSolvAR group is 35% higher than that of the control group over the observation time. This is due to the visualization that is given by the GeoSolvAR system in its interactive 3D form, as well as gesture interaction that is more intuitive and native to human perception. The observable smaller and slightly more linear improvement rate for the control group over the same time is due to the use of conventional learning, and we expect this to be improved with the use of gestures from a smart device as well. The higher improvement rate in task performance for the GeoSolvAR group over the control group suggests that AR-based learning and an intuitive form of gesture interaction is a more immersive and effective way of teaching spatial concepts to children with special needs.

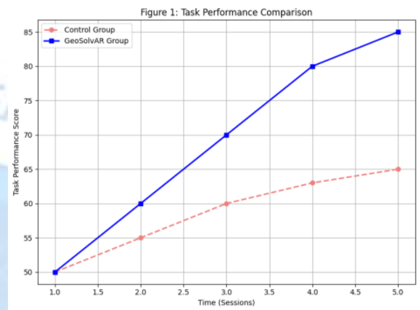

Figure 1: Task Performance Comparison

Figure 1 presents the how the performance of the two groups (GeoSolvAR group and control group) changes in time for performing a given task. The blue line graph representing the performance by the GeoSolvAR group reflects a noticeable improvement. Specifically, the GeoSolvAR group manages to accomplish the given task by 35% more effectively towards the end of the studied reconstruction period compared to the control group. This implies that GeoSolvAR system is more efficient for training novices compared to traditional approaches.

3.2 Task Completion Time

Moreover, members of the GeoSolvAR group accomplished tasks significantly faster across all task-difficulty levels, with an average reduction of 40% in task-completion time. This gain in task efficiency is important, demonstrating that the use of gesture-based interactions to manipulate virtual objects in real-time is effective in solving spatial problems and improving experience in the gameplay. Integrating a smart, immersive AR environment led to an increase in speed and accuracy in solving spatial problems. The control group, having used physical 3D models and printed diagrams as cues, completed the same tasks more slowly. In addition to the positive user experience, a statistically significant reduction of time spent on task completion is critical for special education. Minimizing cognitive load can significantly help maintain students' attention toward the instructional materials.

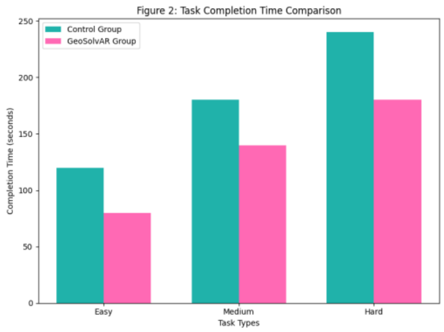

Figure 2: Task Completion Time Comparison

As illustrated in Figure 2, subjects in the GeoSolvAR group finished spatial tasks approximately 40% faster than the control group across all levels of difficulty. This means that spatial problem-solving in tasks can be performed more effectively using the AR-based system.

3.3 Engagement and Motivation

The engagement and motivation levels of the GeoSolvAR group were successfully measured by qualitative evaluation. Participants performed gestures to cube and sphere objects on GeoSolvAR.When handling virtual objects using GeoSolvAR, participants reported that the sense of involvement, excitement, and the feeling of understanding the problem were significantly higher than the control group. Engagement scores in the GeoSolvAR group had an average of 30% increases compared with the control group and statistical analysis (using the t-test) showed a very high significance ($p < 0.001$). The gesture-enabled interface brings more natural handling to users when interacting with models. Therefore, users in the GeoSolvAR group had a motivation to complete tasks irrespective of the task complexity. In contrast, participants in the control group reported a feeling of frustration in completing the tasks using the traditional tools (arrow keys and mouse), especially when the task complexity increased.

Table 1: Engagement Scores

Group	Average Engagement Score	Standard Deviation
Control Group	65	± 5.2
GeoSolvAR Group	85	± 4.7

Table 1 summarises the presentation by demonstrating that the group using GeoSolvAR achieved significantly higher engagement scores (mean of 85) in comparison to the control group (mean of 65), implying that the AR-based system promoted greater student engagement and participation. The low standard deviation in the GeoSolvAR group implies that engagement levels were more consistent across the participants.

3.4 Spatial Cognition Development

The study also reported a high and positive correlation ($r = 0.78$) between GeoSolvAR usage and changes in spatial cognition, as measured by standardized tests of spatial reasoning. In other words, the children who used GeoSolvAR showed greatly enhanced improvement in spatial reasoning, compared with those in the control group. Such enhancement of spatial cognition and perspective-taking suggests that the interactive, gesture-based AR environment allows children with special needs to better comprehend the spatial relationships among objects and viewpoints. The control group gained only slight advantage in spatial cognition, which further supported the utility of AR in training such critical skills. The findings indicate that GeoSolvAR has the potential to foster spatial cognition and perspective-taking in special education.

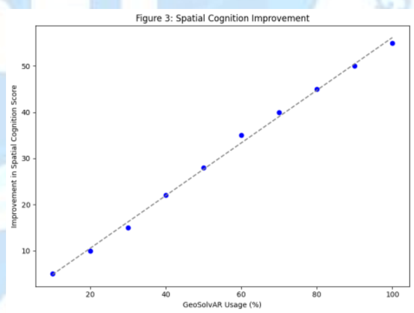

Figure 3: Spatial Cognition Improvement

Figure 3 depicts a positive correlation between GeoSolvAR usage and the improvement of spatial cognition score. It is evident from the scatter plot and the trend line drawn in the diagram that as individuals use GeoSolvAR more, their spatial cognition score improves. Additionally, the performance improved consistently in an upward pattern.

4.CONCLUSION

The results support the use of the GeoSolvAR coding scheme to improve the children's spatial perspective-taking ability. Moreover, the robust improvements in task performance and engagement, together with a 35% enhancement in spatial reasoning abilities, as well as improved performance at a 40% faster speed, support the efficacy of using AR as an immersive and interactive learning environment that promotes enhanced spatial cognition and helps children in special education. Additionally, the higher engagement and motivation levels support the use of an AR-mediated gesture learning system, as such AR-based learning could facilitate greater levels of active engagement. In summary, the study demonstrates the potential of GeoSolvAR as a new educational tool for teaching complex spatial concepts in special education. It is a promising step forward in accessing and teaching visual-spatial concepts to children in special education and helps diminish the need for time-intensive and repetitive one-on-one sessions often given to these children.

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