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Universal design for learning based on augmented reality to enhance spatial and cognitive engagement of neurodivergent students in an inclusive classroom environment

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ABSTRACT

Background: Inclusive education requires learning approaches that can accommodate the diverse cognitive, behavioral, and sensory needs of neurodivergent students, particularly learners with Autism Spectrum Disorder (ASD) and Attention Deficit Hyperactivity Disorder (ADHD). However, conventional classroom instruction often relies on verbal explanation and two-dimensional visual materials, which may limit students' spatial understanding, sustained attention, memory retention, and active participation. Although Augmented Reality (AR) has been increasingly applied in educational settings to enhance visualization and interactivity, its integration with Universal Design for Learning (UDL) principles to support neurodivergent students in inclusive classrooms remains insufficiently explored. This study investigates the implementation of a UDL-based AR learning model to enhance spatial and cognitive engagement among students with ASD and ADHD in an inclusive classroom environment. **Methods:** A mixed-methods approach was employed by combining pretest–posttest assessment, classroom observation, and semi-structured teacher interviews. The participants consisted of ten neurodivergent students, including five students with ASD and five students with ADHD, and two inclusive classroom teachers. **Findings:** Quantitative findings showed improvements across five indicators: spatial recognition, spatial reasoning, cognitive focus, memory retention, and problem-solving accuracy. The highest improvement was found in spatial recognition, followed by problem-solving accuracy and spatial reasoning. Qualitative findings indicated that AR–UDL supported differentiated instruction, increased students' attention, and encouraged more active interaction during learning activities. However, teachers also reported challenges related to classroom management, students' overexcitement, and technical readiness. **Conclusion:** These findings suggest that AR–UDL can serve as a practical and inclusive pedagogical model for supporting neurodivergent learners, especially when implemented with appropriate teacher guidance, ethical consideration, and contextual adaptation. **Novelty/Originality of this article:** This study contributes empirical evidence to the development of technology-supported inclusive education and provides a foundation for future research involving larger samples, longer intervention periods, and comparative experimental designs.

KEYWORDS: augmented reality; cognitive engagement; inclusive education; neurodivergent students; universal design for learning.

1. Introduction

Inclusive education aims to ensure that all students, including learners with neurodevelopmental differences, have equal opportunities to access meaningful learning

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experiences. In inclusive classrooms, students with Autism Spectrum Disorder (ASD) and Attention Deficit Hyperactivity Disorder (ADHD) learn together with their peers in the same educational environment. This approach reflects the principle that learning should be accessible to students with diverse cognitive, behavioral, sensory, and communication profiles. However, the implementation of inclusive education requires more than physical placement in regular classrooms. It also requires learning methods, media, and classroom strategies that can respond to different learning needs. Inclusive education should not be understood only as the physical placement of students with disabilities in mainstream classrooms. It also requires schools to challenge deficit-based perspectives and remove structural barriers that limit students' participation in learning (Liasidou, 2016).

Inclusive education is also grounded in the right of persons with disabilities to access education without discrimination and on the basis of equal opportunity. The Convention on the Rights of Persons with Disabilities emphasizes that persons with disabilities should not be excluded from the general education system and should receive reasonable accommodation and support within inclusive education settings (UN, 2007). Inclusive education has become a major international concern since the Salamanca Statement, and research on inclusive education has continued to expand across countries and educational contexts. However, classroom-based implementation still requires stronger empirical evidence, particularly in relation to how inclusive principles are translated into daily teaching practices (Hernández-torrano et al., 2020). Inclusive classrooms also require supportive school culture and leadership commitment. Inclusive education is strongly influenced by organizational culture, leadership, and the ability of schools to develop collaborative practices (Ainscow & Sandill, 2010).

Students with ASD and ADHD often experience specific learning barriers that require flexible instructional support. Students with ASD may need structured routines, concrete visual representations, repeated instructions, and predictable learning sequences to understand abstract information. Students with ADHD may experience difficulties in sustaining attention, regulating impulses, and maintaining focus during teacher-centered instruction. These challenges become more visible when learning activities rely heavily on verbal explanation, printed materials, or two-dimensional visual media. As a result, neurodivergent students may face difficulties in spatial recognition, spatial reasoning, memory retention, cognitive focus, and problem-solving activities.

In the observed inclusive classroom context, students needed more concrete and interactive visual support, particularly when learning materials involved object identification, size, direction, and spatial relationships. Teachers also reported that students with ADHD tended to lose attention during abstract explanations, while students with ASD required repeated demonstrations and simplified instructions. The learning media used in the classroom were still dominated by conventional materials, such as printed images and verbal explanation. This condition shows a practical gap between the ideal concept of inclusive education and the actual classroom implementation. This gap indicates that inclusive education policies may not automatically result in effective classroom practices when teacher support, instructional resources, and implementation capacity are still limited (Angrist and Dercon, 2024).

Augmented Reality (AR) offers potential support for this problem because it can transform static learning materials into interactive 3D (three-dimensional) objects. Through AR, students can observe, rotate, and explore digital objects in real time, allowing them to build stronger spatial understanding and visual memory. AR-based learning can support students' visualization and engagement by connecting abstract concepts with interactive experiences (Kyza & Georgiou, 2018). For neurodivergent students, this visual and interactive feature is relevant because it reduces dependence on verbal explanation and provides more concrete access to learning materials. However, the use of AR in education should not be treated merely as a technological intervention. If AR is used without a clear pedagogical framework, it may become only an attractive digital tool without ensuring inclusive access for all students. Therefore, AR needs to be integrated with a learning design that supports diverse learning needs. Universal Design for Learning provides this pedagogical foundation by supporting flexible lesson design through multiple forms of representation, engagement, and student expression (Rao & Meo, 2016). These principles help teachers design learning experiences that are more flexible, accessible, and responsive to diverse learners.

The integration of AR and Universal Design for Learning (UDL) is important because AR provides interactive visualization, while UDL ensures that the learning process remains inclusive and structured. AR can help students observe and manipulate 3D (3-dimensional) objects, while UDL guides teachers in presenting information through multiple formats, sustaining student engagement, and allowing flexible ways for students to demonstrate understanding. In this study, AR–UDL is positioned not only as a digital learning medium but also as an inclusive pedagogical model designed to support neurodivergent students in spatial and cognitive engagement.

Previous studies have shown that inclusive education requires adaptive pedagogy, teacher readiness, and supportive classroom environments (Baluyot, 2024). Other studies have also shown that AR has potential to enhance student engagement, visualization, and learning outcomes (Szentirmai & Murano, 2024). However, empirical studies that specifically integrate AR with UDL principles for students with ASD and ADHD in inclusive classrooms remain limited. In particular, few studies have examined how AR–UDL supports spatial recognition, spatial reasoning, cognitive focus, memory retention, and problem-solving accuracy simultaneously. Based on this gap, this study aims to investigate the implementation of a UDL-based AR learning model to enhance spatial and cognitive engagement among neurodivergent students with ASD and ADHD in an inclusive classroom environment. This study also examines teachers' experiences and students' behavioral engagement during AR–UDL implementation. By combining quantitative and qualitative data, this research provides a more comprehensive understanding of the benefits and challenges of AR–UDL learning in inclusive classroom practice.

1.1 Neurodivergent students in inclusive classrooms

Neurodivergent students, including learners with ASD and ADHD, have diverse learning characteristics that require flexible instructional support. Students with ASD may experience challenges in social communication, sensory processing, flexibility, and abstract concept comprehension. They often benefit from visual cues, structured instructions, repeated demonstrations, and predictable routines. Students with ADHD may experience difficulties in attention regulation, impulse control, working memory, and task persistence. These characteristics do not indicate a lack of learning potential; rather, they show the need for learning environments that are more responsive to cognitive and behavioral diversity. The engagement of neurodivergent students is closely related to classroom dynamics, instructional design, and teacher responsiveness. Inclusive pedagogical frameworks are needed to recognize different cognitive and behavioral profiles in classroom learning (Chris & Stephanie, 2024).

Inclusive classrooms require teachers to support neurodivergent students while maintaining meaningful learning for the entire class. This requires differentiated instruction, adaptive learning media, and classroom management strategies. Inclusive education is not only about placing students with special needs in regular classrooms but also about ensuring that learning materials and teaching practices are accessible to them (Florian & Black-hawkins, 2011). Teachers also play an important role in determining whether inclusive classrooms become meaningful learning environments. Teachers often experience dilemmas and frustrations in inclusive education when they do not receive sufficient preparation or practical strategies (Mckay, 2015). Teacher readiness is therefore a crucial factor in implementing inclusive learning innovation. Teachers' readiness influences how inclusive education practices are applied in real classroom contexts, particularly when teachers are expected to adapt instructional strategies for diverse learners (Karynbaeva et al., 2021).

Inclusive education also faces practical challenges, including limited resources, classroom management difficulties, teacher readiness, and the need for differentiated instruction. These challenges show that inclusive classrooms require continuous effort to achieve equity in student participation and learning access (Jardinez & Natividad, 2024).

1.2 Augmented reality in learning

Augmented Reality is a digital technology that overlays virtual objects onto the real-world environment. In education, AR allows students to interact with 3D objects, observe objects from different angles, and connect abstract concepts with concrete visual experiences. This feature is useful for learning activities that require spatial understanding, object recognition, and visual reasoning. Compared with conventional two-dimensional media, AR provides a more immersive and interactive learning experience.AR-based learning can improve students' motivation, attention, and conceptual understanding because it enables active interaction with learning materials (Tian & Ironsi, 2025). For students with Autism Spectrum Disorder, AR has also been explored as a learning support tool because it can provide enhanced visualization, interaction, and structured digital experiences. AR-enhanced learning has potential benefits for children with ASD when the learning design is adapted to their cognitive and behavioral needs (Shemy et al., 2024).

In addition, AR and VR (virtual reality)-based interactive learning systems can strengthen visualization, student engagement, and technology-supported learning experiences when they are designed according to instructional needs (Latif et al., 2024). More specifically, AR can function as a learning scaffold because it helps students connect visual information, textual explanation, and collaborative learning activities. This scaffolding role is important in inclusive classrooms because students need structured support to understand abstract concepts through concrete visual experiences (Yoon et al., 2018).

1.3 Universal design for learning

Universal Design for Learning is an instructional framework designed to reduce learning barriers and provide flexible access for diverse learners. UDL emphasizes three main principles: multiple means of representation, multiple means of engagement, and multiple means of action and expression. These principles are relevant for inclusive classrooms because students can access information, participate in learning, and demonstrate understanding in different ways. UDL supports inclusive learning by shifting the focus from student limitations to learning design. Instead of expecting all students to adapt to one teaching method, UDL encourages teachers to design flexible learning environments from the beginning. For students with ASD and ADHD, UDL can support structured instruction, visual access, repeated explanation, active participation, and differentiated learning tasks (Priyadharsini & Mary, 2024). Future inclusive learning practices should also consider the integration of assistive technology and Universal Design for Learning to support more accessible, flexible, and inclusive instruction for diverse learners (Floyd et al., 2024). UDL can also be understood as a theory of inclusive practice because it helps educators identify and reduce barriers in learning design before those barriers limit student participation (Sewell et al., 2022). UDL is relevant for inclusive classroom practice because its principles support flexible representation, action and expression, and engagement for diverse learners. The implementation of UDL can improve educational outcomes, particularly when the three main principles are applied together in instructional interventions (Almeqdad et al., 2023).

1.4 Integration of AR and UDL

The integration of AR and UDL provides a promising approach for enhancing spatial and cognitive engagement among neurodivergent students. AR supports spatial engagement by allowing students to observe, rotate, and identify 3D objects. UDL strengthens this process by ensuring that AR activities are structured, accessible, and flexible for different learning needs. Therefore, AR–UDL can support both technological and pedagogical dimensions of inclusive education. In this study, AR–UDL is used to support five learning indicators: spatial recognition, spatial reasoning, cognitive focus, memory retention, and problem-solving accuracy. These indicators were selected because they represent important aspects of learning engagement for neurodivergent students in visual and interactive learning environments.

2. Methods

2.1 Research design

This study employed a mixed-methods approach to examine the implementation of an Augmented Reality-based learning model combined with Universal Design for Learning principles in an inclusive classroom environment. A mixed-methods approach was used because the research aimed to measure students' improvement through quantitative data and to understand classroom experiences through qualitative data. Quantitative data were collected through pretest and posttest assessments, while qualitative data were collected through classroom observations and semi-structured teacher interviews. The use of mixed methods allows researchers to combine numerical evidence with contextual classroom interpretation (Creswell & Clark, 2017).

Mixed-methods research is appropriate for educational intervention studies because it allows quantitative outcomes and qualitative experiences to be interpreted together (Johnson & Onwuegbuzie, 2004). The quantitative component measured students' spatial and cognitive engagement before and after the AR–UDL intervention. The qualitative component explored teachers' perceptions, students' behavioral engagement, and implementation challenges during the learning process. The integration of both data sources was used to strengthen the interpretation of the findings.

2.2 Participants

The participants consisted of ten neurodivergent students from an inclusive elementary school in Indonesia. The students included five learners with Autism Spectrum Disorder and five learners with Attention Deficit Hyperactivity Disorder. Two inclusive classroom teachers were also involved in the study as facilitators and interview participants. Participants were selected purposively based on their active involvement in inclusive classroom learning and their relevance to the research focus. Purposive sampling was appropriate because this study required participants with specific learning characteristics and classroom experiences (Palinkas et al., 2015).

Ethical considerations were applied throughout the research process. Parental and institutional consent were obtained before the implementation. The learning activities were conducted under teacher supervision to ensure students' comfort and safety. Any visual documentation involving students should be anonymized, blurred, or presented from angles that do not reveal students' identities.

2.3 Procedures

The research followed four structured stages to ensure the validity and clarity of the implementation process. Needs analysis is Identification of students' learning difficulties and teachers' instructional barriers. Design development is creation of AR-based UDL materials integrating 3D visualization and interactive activities. Implementation is conducting AR–UDL sessions with teacher guidance and real-time observation. Evaluation is collecting posttest results, interviews, and observation data for analysis.

Fig. 1. Pretest results of spatial and cognitive engagement among students with ADHD

The AR–UDL intervention was designed to support students in observing, identifying, and interacting with 3D objects. The teacher provided simplified instructions, repeated explanations, and visual guidance during the learning activities. The intervention applied UDL principles by providing multiple forms of representation, engagement, and student response.

Fig. 2. Implementation of AR–UDL learning in an inclusive classroom environment

2.4 Instruments

Three instruments were used in this study: pretest–posttest assessment, classroom observation sheet, and semi-structured teacher interview guide. The pretest–posttest assessment measured students' spatial and cognitive engagement across five indicators: spatial recognition, spatial reasoning, cognitive focus, memory retention, and problem-solving accuracy. The classroom observation sheet recorded students' attention, interaction, expression, and cognitive participation during AR–UDL sessions. The teacher interview guide explored teachers' experiences, teaching strategies, perceived benefits, and implementation challenges.

2.5 Data analysis

Quantitative data from pretests and posttests were analyzed using descriptive statistics. The mean and standard deviation were calculated to summarize score distributions, while improvement was measured using the following formula:

$$\text{Improvement (\%)} = \frac{\text{Posttest} - \text{Pretest}}{\text{Pretest}} \times 100\% \qquad \text{(Eq. 1)}$$

For example, if the pretest score is 55 and the posttest score is 82, the improvement is:

$$\text{Improvement (\%)} = \frac{82-55}{55} \times 100\% \qquad \text{(Eq. 2)}$$

The mean score was calculated using the following formula, where X = mean score, ΣXi = total score, N = number of students

$$\frac{\Sigma_{\mathrm{i}}^{\mathrm{N}}{=}_1 X_i}{N} \qquad \text{(Eq. 3)}$$

The standard deviation was calculated using the following formula, where SD = standard deviation; Xi = individual score; X = mean score; and N = number of students.

$$SD = \frac{\sqrt{\Sigma(Xi-X)^2}}{\mathrm{N}-1} \qquad \text{(Eq. 4)}$$

A smaller standard deviation indicates more consistent results among participants, while a larger standard deviation indicates greater variation in students' scores. Qualitative data from interviews and observations were analyzed using thematic analysis to identify recurring themes related to teacher adaptation, student engagement, and AR–UDL implementation challenges (Braun et al., 2008).

3. Results And Discussion

3.1 Improvement of students' spatial and cognitive engagement through AR–UDL

The quantitative results showed improvements in students' spatial and cognitive engagement after participating in AR–UDL learning activities. Table 1 presents the mean and standard deviation scores obtained from the pretest and posttest assessments.

Table 1. Assessment results

No	Indicator	Pretest Score (Mean ± SD)	Posttest Score (Mean ± SD)	Improvement (%)
1	Spatial recognition (object identification)	55.2 ± 10.3	82.5 ± 8.7	49.5

No	Indicator	Pretest Score (Mean ± SD)	Posttest Score (Mean ± SD)	Improvement (%)
2	Spatial reasoning (size/direction understanding)	58.0 ± 9.5	84.1 ± 7.8	45.0
3	Cognitive focus (attention span)	62.3 ± 11.1	86.7 ± 6.9	39.1
4	Memory retention (object recall)	59.7 ± 10.6	83.2 ± 8.4	39.4
5	Problem-solving accuracy	54.9 ± 9.2	80.8 ± 7.2	47.2

3.2 Calculating mean and SD for spatial recognition

The results show that all indicators improved after the implementation of AR–UDL learning. Spatial recognition showed the highest improvement, increasing from 55.2 ± 10.3 to 82.5 ± 8.7. This indicates that the AR-based 3D visualization helped students identify and understand object components more clearly. This finding supports the view that AR can strengthen learning visualization through interactive digital objects (Szentirmai & Murano, 2024).

Spatial reasoning also improved from 58.0 ± 9.5 to 84.1 ± 7.8. This improvement suggests that students were better able to understand size, direction, and object relationships after interacting with AR materials. Unlike static two-dimensional images, AR allowed students to observe objects from different perspectives. This helped students build stronger spatial understanding through direct visual exploration.

Cognitive focus increased from 62.3 ± 11.1 to 86.7 ± 6.9. This result indicates that AR–UDL activities helped students sustain attention during learning. The interactive object functioned as an attention anchor, especially for students with ADHD who often experience difficulties maintaining focus during conventional instruction. However, the observation data also showed that teacher guidance was needed to prevent students from becoming overly excited.

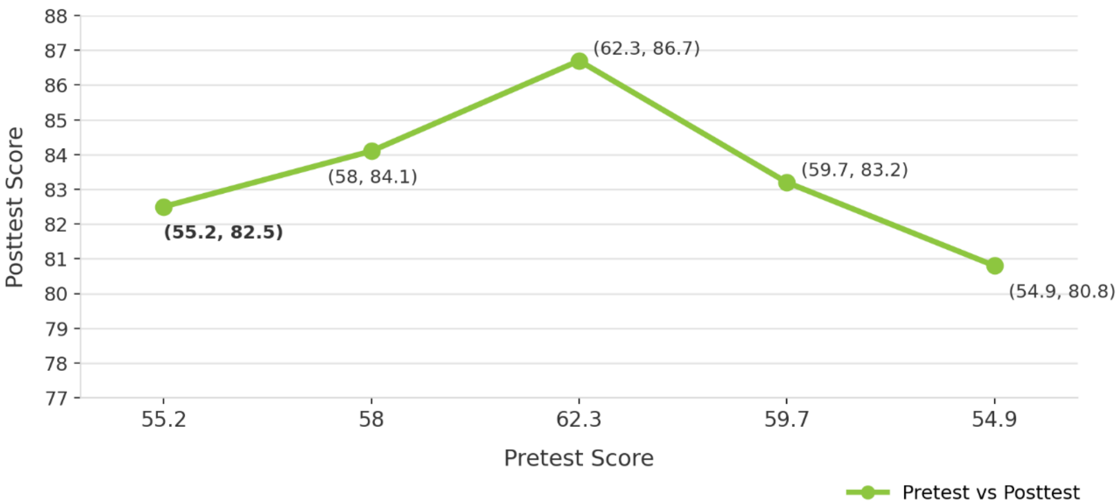

Fig. 3 Pretest and posttest results

Memory retention improved from 59.7 ± 10.6 to 83.2 ± 8.4. This finding indicates that students were able to recall learning objects more effectively after interacting with visual and interactive materials. The use of multiple representations in UDL helped students access information through visual, verbal, and active learning pathways (Priyadharsini & Mary, 2024). Problem-solving accuracy increased from 54.9 ± 9.2 to 80.8 ± 7.2. This suggests that students were not only more interested in learning but also better able to complete learning tasks. AR–UDL supported students in connecting object visualization with cognitive task completion. Therefore, the model contributed to both engagement and learning performance.

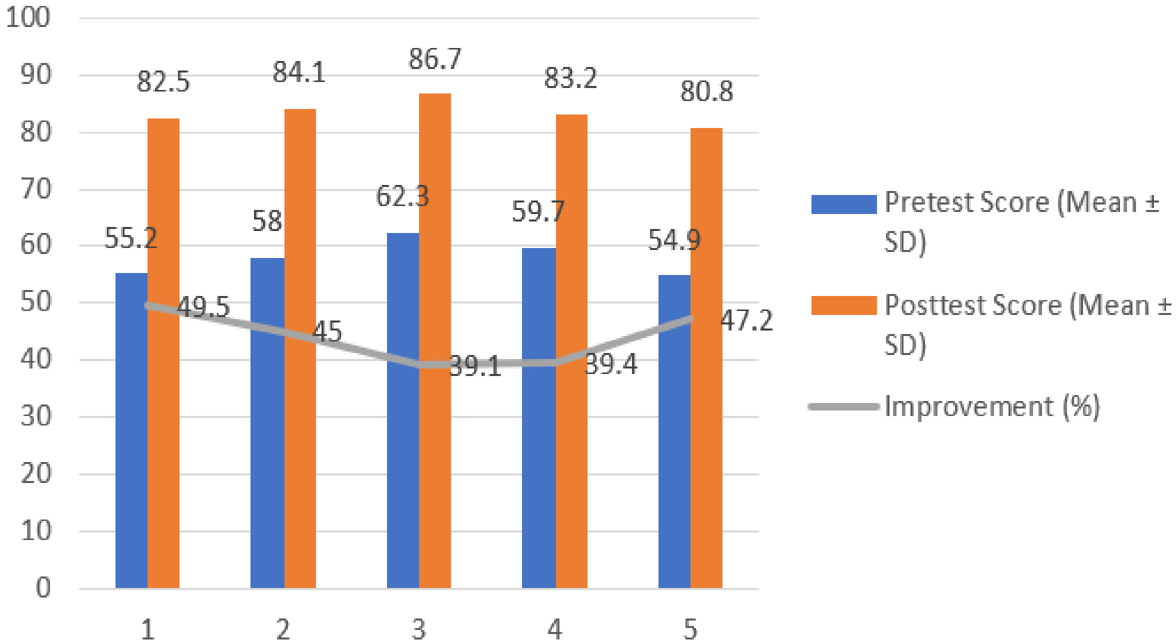

Fig. 4. Improvement of students

Information: (1) Spatial recognition (object identification), (2) Spatial reasoning (size/direction understanding), (3) Cognitive focus (attention span), (4) Memory retention (object recall), (5) Problem-solving accuracy.

3.2 Teachers' experiences and perceptions of AR–UDL implementation

Qualitative data obtained through semi-structured interviews with inclusive classroom teachers further supported the quantitative findings. Teachers' reflections indicated that AR–UDL integration supported better engagement, although several technical and classroom management challenges appeared during implementation.

Table 2. Teachers' experiences and perceptions of AR–UDL implementation

Theme	Description	Example Quote
Challenges	Teachers experienced technical difficulties and difficulties maintaining focus among students with ADHD.	"Some students get too excited when they see the 3D planes, so it takes time to calm them down."
Teaching Strategies	Teachers used repetition, simplified language, and visual aids for students with autism.	"I repeat the instructions in simple language and show them directly on the screen so the child understands better."
Impact of AR Application	Teachers observed increased focus, interest, and interaction during AR sessions.	"Usually they get bored quickly, but this time they could focus for a long time because they could see and move the plane themselves."

Teachers' feedback showed that AR–UDL helped them provide differentiated instruction for students with different cognitive profiles. The use of 3D visualization made it easier for teachers to explain object components and spatial relationships. This was particularly helpful for students with ASD who needed repeated visual demonstrations. The teachers also reported that AR increased students' interest and attention during learning. Students who were usually passive became more willing to observe, respond, and interact with the learning media. This finding supports the argument that digital learning tools can increase classroom interaction when they are supported by teacher guidance (Al-khresheh et al., 2025).

However, teachers also noted that AR implementation required classroom management strategies. Some students became overly excited when the 3D object appeared on the screen. This condition required the teacher to pause the activity, repeat the instructions, and manage turn-taking. Therefore, AR–UDL should be implemented with clear routines and structured guidance.

3.3 Behavioral engagement observation

Behavioral observation data further supported the quantitative and interview findings. The overall mean engagement level was 4.3 out of 5, indicating a high degree of active participation and focus among students during AR–UDL learning sessions.

Table 3. Behavioral engagement observation

No	Observation Aspect	Behavioral Indicator	Engagement Level (1–5)	Notes
1	Attention & Focus	Maintaining eye contact, following teacher instructions	4.6	Students remained focused and attentive during AR simulations.
2	Interaction	Responding to questions, collaborating with peers	4.2	Students actively engaged in group activities and discussions.
3	Expression	Demonstrating enthusiasm and mimicking aircraft sounds	4.0	Students expressed excitement while handling AR markers.
4	Cognitive Participation	Correctly identifying aircraft parts	4.4	Students accurately named and pointed out aircraft components.

Student engagement should be interpreted through observable participation, attention, interaction, and learning involvement. Engagement assessment can be strengthened by analyzing qualitative evidence related to student learning behavior (Ahmed et al., 2025). The observation results showed that students demonstrated strong attention, interaction, emotional expression, and cognitive participation during AR–UDL learning. The highest score was found in attention and focus, with an engagement level of 4.6. This indicates that AR visualization helped students maintain attention during the learning activity.

Table 4. Assessment criteria

Score	Engagement Categories	Information
1	Not engaged	Shows no interest or participation
2	Minimally engaged	Low attention, passive participation
3	Moderately engaged	Moderate focus, moderate participation
4	Actively engaged	Focused and actively involved
5	Fully engaged	Very focused, fully participati

Cognitive participation also received a high score of 4.4. Students were able to identify aircraft parts and respond to teacher questions more accurately during the AR session. This supports the quantitative finding that spatial recognition and problem-solving accuracy improved after the intervention. The interaction score reached 4.2, indicating that students were actively involved in group activities and discussions. This shows that AR–UDL did not only support individual learning but also encouraged classroom participation. Inclusive learning should provide opportunities for students to participate meaningfully with their peers (Baluyot, 2024).

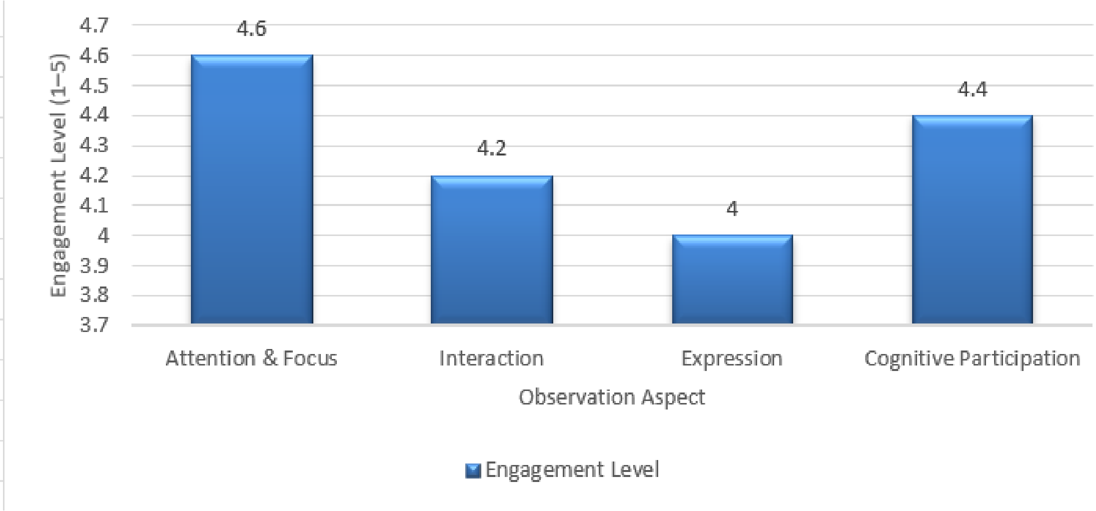

Fig. 5. Engagement level per observation aspect

The expression score reached 4.0. Students showed enthusiasm while handling AR markers and interacting with the visual objects. However, the teacher needed to manage this excitement so that students remained focused on the learning objectives. This finding shows that engagement should be balanced with classroom structure.

Fig. 6. Comparison of pretest and posttest spatial and cognitive engagement among students with ADHD

3.4 Integrated discussion

The integration of quantitative, interview, and observation data indicates that AR–UDL supported students' spatial and cognitive engagement in an inclusive classroom. The pretest–posttest results showed measurable improvement across all five indicators. Teacher interviews explained how AR visualization helped simplify instruction and sustain students' attention. Classroom observations confirmed that students were actively involved during the learning process. The improvement in spatial recognition can be explained by the ability of AR to present objects in 3D and interactive forms. Students could observe and identify object components more directly than when using printed images. This helped them build stronger visual understanding. The improvement in spatial reasoning also indicates that students benefited from observing object direction, size, and position through AR-based visualization.

The improvement in cognitive focus suggests that AR can support attention when used with structured learning guidance. For students with ADHD, interactive learning objects may reduce passive learning and increase task involvement. However, teacher control remains important because AR can also produce excessive excitement. Therefore, AR should be combined with clear rules, short instructions, and guided tasks. The improvement in memory retention and problem-solving accuracy shows that AR–UDL supported deeper learning participation. Students were not only observing objects but also recalling information, answering questions, and completing learning tasks. This finding indicates that UDL can support flexible access to learning by providing multiple means of representation, engagement, and action or expression for diverse students (Rao & Meo, 2016).

The interpretation of the findings should focus not only on score improvement but also on how the learning process becomes visible through classroom interaction and teacher guidance. Therefore, the improvement in students' spatial and cognitive engagement should be interpreted not only through posttest scores, but also through classroom interaction, teacher feedback, and instructional clarity during the AR–UDL implementation (Hattie, 2012). These findings also indicate that AR–UDL requires teacher readiness and institutional support. Technology may improve engagement, but its effectiveness depends on the ability of teachers to manage classroom interaction, provide scaffolding, and adapt instruction to students' needs. Inclusive pedagogy should recognize neurodiversity and reduce barriers that limit students' meaningful participation in classroom learning (Cook, 2024). Overall, the findings show that AR–UDL is not only a technological tool but also a pedagogical model. AR provides interactive visualization, while UDL ensures that the learning process remains inclusive, structured, and accessible. Therefore, AR–UDL can be considered a practical approach to support neurodivergent students in inclusive classroom environments.

4. Conclusion

This study investigated the implementation of a Universal Design for Learning-based Augmented Reality model to enhance spatial and cognitive engagement among neurodivergent students with Autism Spectrum Disorder and Attention Deficit Hyperactivity Disorder in an inclusive classroom environment. The findings showed that students' engagement improved across all measured indicators, including spatial recognition, spatial reasoning, cognitive focus, memory retention, and problem-solving accuracy. The highest improvement occurred in spatial recognition, which increased by 49.5%. This suggests that AR-based 3D visualization was particularly useful in helping students identify and understand object components. Problem-solving accuracy and spatial reasoning also showed strong improvements, indicating that AR–UDL supported both visual understanding and cognitive task completion.

Teacher interviews showed that AR–UDL helped simplify instruction, increase students' attention, and encourage active participation. Classroom observations also confirmed that students demonstrated strong behavioral engagement, with an overall engagement level of 4.3 out of 5. These findings indicate that AR–UDL can support inclusive learning by combining interactive technology with flexible pedagogical design.

However, this study also found several implementation challenges, including students' overexcitement, classroom management issues, and technical readiness. Therefore, AR should not be implemented as a standalone tool. It requires teacher guidance, structured routines, ethical consideration, and appropriate classroom preparation. Overall, this study contributes empirical evidence to the field of technology-supported inclusive education. It demonstrates that AR–UDL has the potential to enhance spatial and cognitive engagement among neurodivergent learners while supporting differentiated instruction in inclusive classrooms.

This study has several limitations. First, the sample size was relatively small and involved only one inclusive school, which limits the generalizability of the findings. Second, the intervention was conducted within a limited classroom context, so long-term retention and sustained behavioral changes could not be fully examined. Third, this study did not use a control group, making it difficult to compare AR–UDL learning directly with conventional instruction. Fourth, the implementation depended on device availability and teacher readiness, which may vary across school contexts. Future research should involve larger and more diverse samples from multiple inclusive schools. Further studies should also use experimental or quasi-experimental designs with control groups to provide stronger evidence of effectiveness. Longitudinal research is also needed to examine whether improvements in spatial and cognitive engagement can be sustained over time.

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Author Contribution

Conceptualization, A.D.F and B.B.; Methodology, A.D.F.; Software, A.D.F and H.D.; Validation, A.D.F; Formal Analysis, A.D.F and H.D.; Investigation, A.D.F and H.D.; Resources, A.D.F; Writing – Original Draft Preparation, A.D.F and H.D..; Writing – Review & Editing, A.D.F and H.D.; Visualization, A.D.F and H.D.

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Ethical Review Board Statement

Not available.

Informed Consent Statement

All photographs included in this manuscript were obtained with the necessary permission and informed consent from the individuals depicted. Permission was granted for the photographs to be used and published as part of this manuscript.

Data Availability Statement

Not available.

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author used ChatGPT to assist in improving language clarity, academic writing structure, and coherence of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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