

Augmented Reality Applications for Skill Development in Children with Learning Disabilities

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ABSTRACT:

Learning disabled children usually have problems in concentration, understanding and learning skills, which restrict their educational and social growth. The conventional instructional techniques do not often tend to cater to different learning needs, and this leaves a huge gap in inclusion education. In this paper, the researcher will examine how the use of Augmented Reality (AR) as an innovative intervention can be used to improve the development of skills among children with learning disabilities. The suggested methodology will be a combination of AR-based interactive modules that will enhance

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literacy, numeracy, memory, and motor coordination skills. The research methodology involves designing adaptive AR learning environments, usability tests and experimental analysis involving a controlled group of learners. The data were gathered based on performance indicators, level of engagement, and cognitive response. An example of primary school children illustrates how activities based on AR enhance the rate of task completion and retention compared to traditional activities. Analytical results show great improvement in learning involvement, accuracy, and conceptual knowledge, and measurable gains in attention and motivation. The findings show that AR supports multisensory learning to allow individual and rich learning experiences. This paper has gone further to include the scope of inclusive education systems, rehabilitation programs and assistive learning technologies. Other challenges highlighted include the cost, accessibility, and teacher training needs. To sum up, AR-based learning systems have the potential to become an effective tool that can help address educational gaps and promote skill acquisition among children with learning disabilities.

Keywords: Augmented Reality, Learning Disabilities, Inclusive Education, Skill Development, Assistive Technology, Cognitive Enhancement.

I. Introduction

- **Background on Learning Disabilities and Educational Challenges**

Learning disabilities are a heterogeneous group of neurological disorders that impact negatively on the acquisition, organisation, retention, understanding and utilisation of verbal and non-verbal information (Fernandez-Batanero et al., 2022). It is estimated that 15-20 percent of children of school-going age in the world have some type of learning disability, such as dyslexia, dyspraxia, dyscalculia, attention deficit hyperactivity disorder (ADHD) and Autism Spectrum Disorder (ASD). These disorders appear in a spectrum of degrees of severity and seldom exist separately, but they tend to be interrelated and exacerbate each other to form complex educational issues (Quintero et al., 2019). The academic effects of learning disabilities that go undiagnosed are devastating: students often underperform, their self-efficacy declines, anxiety and social marginalisation become widespread (Kapetanaki et al., 2022). The conventional pedagogical models, which are, to a

large extent, oriented towards neurotypical students, rely on the ability to follow a sequence of verbal and written messages, abstract symbolic reasoning, and long attention spans - the very aspects, where children with learning disabilities show the weakest results. Standardised curricula, big classes and the lack of specialist resources only deter the capacity of educators to deliver the differentiated instruction these learners need. The outcome is a persistent achievement gap that continues to perpetuate series of disadvantages and sabotage the underlying pledge of inclusive education. The need to close this gap requires pedagogical change as well as strategic implementation of assistive technologies that can adjust to the various cognitive profiles of learners with disabilities.

- **Need for Innovative Assistive Technologies**

The shortcomings of traditional assistive technologies, such as fixed visual aid, audio resources that are static and pre-recorded, and simple, computer-aided instructions, have led to

continuous concern about more interactive and responsive technologies (Chitu et al., 2023). Although the legacy assistive technologies offered valuable functionality in limited areas, they mostly did not offer the real-time adjustment, multisensory stimulation, and customisation of learners, which current research defines as the key to effective special education (Yenioglu et al., 2023). With the advent of immersive technologies, especially Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), new transformative opportunities have been created with regards to how children with various learning needs can access educational material. AR, potentially positioned between these technologies as an interface allowing the addition of digital content to the real-world environment either via handheld devices, tablets, or wearable headsets, uniquely enjoys the benefits of maintaining contextual real-world information and adding interactive, multisensory digital information (Zhu et al., 2023). In contrast to VR, AR does not remove the learner out of the real world (physical and social), which is especially relevant because the learning of children, whose learning is tied to a familiar setting, routine, and interactions with peers. The visual, auditory and kinesthetic abilities of AR to scaffold learning simultaneously meets the core processing gaps of most learning disabilities that make it a promising choice in next-generation inclusive educational interventions.

- **Role of Augmented Reality (AR) in Education**

AR has quickly developed beyond a small tech that was exclusively linked with entertainment to a meaningful educational resource, having proven its effectiveness in a variety of learning environments (Lin et al., 2016). Particularly in special education, AR has been used to facilitate the development of literacy and language, acquisition of numeracy skills, social skills training, motor coordination, and emotional awareness - virtually the entire range of skills that children with learning disabilities are not able to develop using conventional approaches (Doulah et al., 2023). Recent systematic reviews of empirical studies consistently report positive results, such as better task engagement, quicker skill acquisition, better retention, and increased learner

autonomy in instructional activities when AR is used in instructional activities (El Shemy et al., 2024). In children with ASD, AR applications have demonstrated specific potential to teach recognition of facial expressions, turn-taking, and conversational skills by incorporating socially relevant stimuli in the context of controlled, repeatable interactive situations (Wedyan et al., 2021; Sun et al., 2024). In the case of children with dyslexia, reading interventions based on AR have been identified to decrease the cognitive load of decoding through the use of dynamic phonemic scaffolds and instant corrective feedback (Mokmin et al., 2025). In children with motor and spatial disabilities, AR worlds have been effective in helping them to develop fine motor coordination and spatial reasoning via embodied, gesticulated interactions (Yang et al., 2025). Together, these results position AR as a flexible, evidence-based technology that has the potential to deal with the scope of issues presented by learning disabilities in one, unified, integrated pedagogical approach.

- **Research Objectives and Contributions**

There are four main research objectives of this paper. First, it methodically reviews and summarises available evidence on the use of AR applications with children with learning disabilities, outlines trends in efficacy, prevalent methodological constraints, and unexplored populations. Second, it suggests a theoretically based and architecturally elaborated AR-based learning model that is specifically aimed at tackling the literacy, numeracy, motor, and social skills development of primary school children with learning disabilities. Third, it offers the empirical results of a controlled experimental case study that assess the effect of the framework on the results of engagement, accuracy, retention, and cognitive development. Fourth, it critically analyzes the challenges in practice and systemic barriers of large-scale AR implementation in special education with evidence-based recommendations on how to implement it. The main findings of the research are a detailed literature review consisting of twelve studies, a new three-layer AR system design, and a deep dataset of quantitative results that contribute to the development of the evidence base of technology-

enhanced inclusive education. The paper will provide scholars, teachers, and policymakers with the necessary skills to implement AR-based interventions in various educational institutions by connecting theoretical frameworks and evidence relating to their practical implementation.

II. Literature Review

The history of assistive learning technologies shows a movement towards more complex adaptive platforms that can dynamically adjust in response to the specifics of a learner (i.e. text-to-speech, audio books, enlarged-print materials, etc.) to more complex adaptive learning technology (e.g. text-to-speech software, audio books, etc.). Initial computer-assisted instruction programmes yielded small improvements in basic literacy and numeracy with children with mild-to-moderate learning disabilities, but were mostly limited due to their linear non-adaptive design and to a narrow range of sensory modalities. The introduction of tablet-based applications increased the accessibility and interactivity of online learning tools, and introduced touch-interfaces that decreased the motor requirements of conventional keyboard and mouse interaction. Nonetheless, the spreading of general-purpose educational applications without particular focus on the learners with disabilities has produced uneven results, and most of the tools do not address the attentional, sensory, and executive functions profiles of the conditions, including ASD, ADHD, and dyslexia (Kapetanaki et al., 2022). A study by Chitu et al. (2023) emphasized the increasing possibilities of immersive technologies - especially VR and AR - to overcome the constraints of previous assistive devices through providing embodied and contextually rich and multisensory learning experiences. Such technologies have the potential to provide information in parallel through visual, auditory and proprioceptive means, directly addressing the multisensory integration impairments that are the cause of most learning disabilities. Bryant et al. (2025) also showed that clinically meaningful improvements in language and communication abilities in children with developmental communication disabilities could be obtained with purpose-designed AR applications,

co-designed with end-users and their educators, highlighting the significance of participatory design in this area.

AR literature in the field of special education has grown dramatically in the last ten years due to the rising technological accessibility as well as the rising acknowledgment of the pedagogical possibilities of AR in the varied learner population. Doulah et al. (2023) have performed a thorough systematic review of the AR interventions with children with ASD, identifying 34 studies published between 2013 and 2023 and recording the positive results in the outcomes of communication, social interaction, and task engagement. Equally, Yenioglu et al. (2023) have conducted a synthesis of 41 studies on AR in the field of special education, in general, and found that AR had a positive impact on learning engagement in children with ASD and intellectual disability. In an extended corpus of research tracing the development of AR in the context of educational inclusion over a decade, Quintero et al. (2019) discovered that the use of AR applications was linked to increased levels of participation, motivation, and generalisation of skills in an inclusive classroom. Zhu et al. (2023) have implemented a scoping review specifically on people with intellectual disabilities with the capacity of AR to provide assistance in the daily living skills, vocational training, and literacy development with the help of visual scaffolding and step-by-step guidance overlays. The preliminary experimental results presented by Lin et al. (2016) indicated that AR-enhanced activities were much more effective than regular teaching in improving motor and cognitive skills among children with mixed disabilities. More recent domain specific reviews have further honed the evidence base: Yang et al. (2025) reported spatial skills improvements in mathematics learning with the help of AR; Mokmin et al. (2025) reported better reading engagement in dyslexics using AR-based physical education instruction; and Mittmann et al. (2023) reported promising but methodologically heterogeneous evidence of AR-mediated social skills development in children. The latest systematic syntheses were presented by El Shemy et al. (2024) and Fuentes et al. (2025) who reported vocabulary and language

gains in ASD children using AR-enhanced language learning tools and cognitive outcomes such as attention, memory, and executive function across various AR-based ASD interventions, respectively. Khoirunnisa et al. (2023) and Sun et al. (2024) provided comprehensive design and evaluation research of AR reading and social skills interventions to be used with ASD groups, whereas Wedyan et al. (2021) provided comprehensive experimental research on AR-mediated facial expression recognition. Taken collectively, this is a powerful, although still developing mass of evidence regarding AR as a revolutionary technology in special education.

Although the literature shows encouraging trends, there are a number of sizeable gaps and methodology limitations that limit the existing evidence base. Most significantly, most of the reviewed studies use small and non-representative samples that cannot provide statistical power and cannot be generalised. Research designs often do not include randomised control groups, and it may be challenging to attribute any improvement observed to AR as opposed to the effect of increased attention and novelty effects caused by any new technology (Pimple et al, 2025). There are limited longitudinal data available on the retention of skills and their generalisation after the immediate post-intervention period and most studies are limited to single-session or short-term interventions. Moreover, the attention to the ASD populations is high, and the evidence on children with dyslexia, dyscalculia, ADHD, and motor disabilities is relatively low (Yenioglu et al., 2023; Fernandez-Batanero et al., 2022). Cross-study

comparison is complicated by the heterogeneity of AR platforms, content type, delivery forms, and outcome measures across studies and hinders the production of comprehensible and practical educator and developer guidelines. There is a well-recognised and minimal operationalisation of cost, device accessibility, and teacher competency barriers as study variables, which impedes the ecological validity of results. Kapetanaki et al. (2022) particularly identified the lack of training systems in teachers and caregivers as a crucial gap in translating AR research into classroom activities.

The above review of the literature inspires the present study in a number of ways. The consistently low scores in the achievement of children with various learning disabilities and the proven yet underutilized potential of AR as an inclusive educational technology provide a definite incentive to conduct a study that develops, implements, and assesses a full-fledged AR-based skill development model. The gaps outlined above, especially the lack of multi-domain AR interventions to cover literacy, numeracy, motor, and social skills at the same time; the absence of controlled experimental studies; and the unavailability of long-term retention outcomes all have a direct influence on the design priorities of the proposed framework. It is with the aim of filling these gaps with a theoretically-informed architecture, a systematic experimental approach and a case study carried out in an ecologically-authentic school context that this paper hopes to provide a substantive contribution to the science as well as practice of AR-enhanced inclusive education.

Table 1: Summary of Key Literature on AR for Learning Disabilities

Author(s)	Focus Area	Methodology	Population	Key Findings	Limitations
Doulah et al. (2023)	ASD Interventions	AR systematic review	Children (ASD)	Communication gains	Limited sample size
Yenioglu et al. (2023)	Special Education AR	Systematic lit. review	K-12 special ed.	Engagement improved	Mostly qualitative
Quintero et al. (2019)	Educational Inclusion	Systematic review	Diverse disabilities	Inclusion outcomes	Heterogeneous tools
Zhu et al. (2023)	Intellectual Disability	Scoping review	Adults & children	Assistive tech value	Narrow scope
Lin et al. (2016)	Disability Activities	Experimental study	Children (mixed)	Motor/literacy gains	Small cohort

Yang et al. (2025)	Math Spatial Skills	Scoping review	Primary students	Spatial reasoning↑	Math-domain only
Mokmin et al. (2025)	Dyslexia/PE	Mixed-methods	Dyslexic students	Reading engagement	PE context only
Mittmann et al. (2023)	Social Skills ASD	Scoping review	Children (ASD)	Social skill gains	Generalization gap
Bryant et al. (2025)	Communication Disability	Dev. & evaluation	Children (CDD)	Language outcomes	Prototype stage
El Shemy et al. (2024)	ASD Language Learning	Systematic review	Children (ASD)	Vocabulary gains	App variability
Fuentes et al. (2025)	ASD Cognitive Outcomes	Systematic review	Children (ASD)	Cognition improved	Methodological gaps
Kapetanaki et al. (2022)	Special Education AR	Systematic review	Special ed. students	Multi-skill gains	Tech cost barriers

III. AR-Based Learning Framework Design

The suggested AR learning model is a multilayered, systematic system that will provide children with learning disabilities with adaptive, multisensory, educational interventions in the primary school. The framework combines data management, interactive in real-time, and responsive feedback systems to form a personalised, inclusive learning experience that reconciles the digital scaffolding and physical classroom experience.

- **Architecture of the AR Learning System**

The AR learning system has three layers that are interdependent; the Data Layer, the Interaction Layer and the Feedback Layer. The Data Layer is the brain of the system, which combines the learner profiles, disability types, pre-assessment scores, and the history of interactions between the system and the learner to construct the dynamically adjustable content difficulty, modality preferences, and pacing parameters of every learner. The data on learners is stored in a privacy-compliant cloud storage, which is constantly updated with the help of the analytics of sessions. The Interaction Layer is the most user facing element that provides AR content in either tablet based or head-mounted interfaces. Digital overlays of the three dimensional type, such as animated characters, interactive objects, phonemic prompts and step-by-step motor guidance animation are overlaid on real-world materials

(books, worksheets and physical manipulatives) so that learners can use natural gesture and tactile input to engage with the augmented content. The Feedback Layer is a component that completes the instructional loop by delivering multimodal feedback (visual rewards, auditory reinforcement, haptic alerts, and so on) in real time in direct correspondence to learner behavior, pattern of errors, and performance benchmarks. Feedback is adjusted to the emotional regulation profile of each learner so as not to overstimulate them especially in children with ASD. The combination of the three layers facilitates an ongoing, adaptive learning process that is responsive to learner performance, maintains engagement and skill consolidation with repeated exposures.

- **Development of AR Modules for Literacy, Numeracy, and Motor Skills**

The framework involved four independent AR modules that focused on a particular area of development that is deemed high priority to children with learning disabilities. The Literacy Module uses AR-enhanced storybooks where animated characters read the stories, phonemic overlays can be used to show the letter-sound correspondence and interactive hotspots can be used to investigate the vocabulary with the help of contextual images and audio pronunciation. The Numeracy Module introduces the idea of arithmetic and spatial reasoning by simulating three-dimensional manipulative activities where a learner

can physically manipulate virtual objects to rearrange and regroup them to learn about mathematical connections. The Motor Skills Module involves a gesture-recognition technology to direct learners through fine motor sequences - including letter formation, object manipulation - with real-time visual tracings which give corrective feedback when the target trajectories are exceeded. The Social Skills Module offers virtual social interactions, such as face recognition tasks, simulating conversations, and identifying emotions, based on the methods demonstrated to be effective by Wedyan et al. (2021) and Sun et al. (2024), reconfigured to work with AR glasses to overlay face expression labels and emotion indicators over the actual interactions between a student and peers in a classroom. The special education teachers and occupational therapists co-designed all modules to make sure that the curricula were aligned with therapy and were relevant.

- **Personalisation and Adaptive Learning Mechanisms**

The personalisation in the framework is realised in a dual-layer adaptive algorithm, which works in both the content selection and the difficulty calibration level. On the content level, the algorithm will pick AR stimuli, i.e., visual density, animation speed, complexity of audio, and amount of text, depending on the disability profile of a particular learner, sensory preferences, and history of previous performance. The algorithm at the difficulty level uses a dynamic zone-of-proximal-development model, which is automatically progressed, preserved or diminished in task difficulty depending on the accuracy rollout rates of the past five trials. Students with a score of above 80 percent accuracy on a task variant are promoted to the next level of difficulty; students with a score of less than 60 percent are provided with further scaffold support and then they are allowed to proceed with tasks. Adaptive branching pathways will make sure that no learner has to repeat failure, which will be designed based on the self-efficacy literature and operationally justified by the results of Fuentes et al. (2025) and Yenioglu et al. (2023). Teacher dashboards give a real-time view of individual and group performance and allow the instructor to overrule the algorithmic

suggestions and tailor the learning trajectory in response to observational information that the system is unable to record.

- **Integration with Classroom Environments**

Implementation of AR in special education classrooms would be successful only after it is properly integrated with the routines of the classroom, its physical space, and the way the classroom is taught. The system was intended to be used on the typical school-provided tablets (iPads and Android devices) and inexpensive AR glasses, thus allowing the school to avoid the purchase of specialized hardware. AR content is activated by printing marker cards in the middle of existing classroom materials, which enables the teachers to enable AR overlays when performing normal reading and maths lessons, without disruption of classroom instruction. The wireless classroom management software allows teachers to control all devices of learners through one console, pause or redirect activities, and to send individual encouragement messages. The modules on professional development have been designed in collaboration with the teachers of three pilot schools and help teachers to incorporate AR activities into their everyday routine, understand the dashboard analytics, and modify AR activities to meet the needs of students with complex requirements. The integration model is consistent with the ideas of Kapetanaki et al. (2022) about the systemic teacher education and is based on the principles of co-design popularized by Bryant et al. (2025) when creating the InterPlay language learning application.

IV. Methodology

- **Experimental Design and Participant Selection**

A quasi-experimental pre-test, post-test, and delayed retention assessment using mixed-methods design was used. The sample was a group of 68 primary school children aged 7-12 years in an urban environment all with a clinically identified learning disability, ASD ($n = 24$), dyslexia ($n = 18$), ADHD ($n = 14$) and mixed learning difficulties ($n = 12$). The participants were randomly assigned to an AR

intervention group ($n = 34$) and an instruction control traditional group ($n = 34$) that were matched in terms of age, disability classification and baseline academic performance. The content of the curricular material was the same in both groups, and the length of the intervention period was twelve weeks; AR group was taught the material under the AR learning framework, whereas the control group was taught the same material with the use of the usual textbook and worksheet material with the addition of the teacher-led demonstration. All parents and the legal guardians were informed and a written consent was obtained before enrolment. Children who had severe co-morbid physical disabilities that would have meant they could not interact with the device were not included in the study and those with a history of seizure disorders that were contraindicated with the use of interactive screens were also not allowed to participate in the study.

- **Data Collection Techniques**

The collections of data were made along three kinds of outcome measures. The AR platform automatically recorded performance metrics (accuracy rates of the tasks, response times, task completion scores) at the session level and summarized per week. The engagement metrics, including on-task time, voluntary rates of re-engagement, percentage of session completion, rating of motivation on a pictorial Likert scale modified to use with children, were captured based on a mix of platform analytics and structured teacher observation guidelines. The cognitive measures, such as, working memory capacity, selective attention, spatial reasoning, and fine motor coordination were evaluated with the help of standardised neuropsychological measures at the baseline (Week 0), during intervention (Week 6), after the intervention (Week 12), and delayed retention (Weeks 14 and 16). Structured teacher observation checklists which were completed at two-week intervals during the intervention period were used to gather observational data on social interaction, behavioural regulation, and collaborating with peers. The qualitative data on perceived usability, acceptability, and practical

issues in the implementation were complemented by semi-structured interviews with teachers and parents.

- **Tools and Technologies Used**

The AR intervention was presented with the help of tablets (iPad Pro 12.9-inch and Samsung Galaxy Tab S8) and lightweight AR glasses (Microsoft HoloLens 2 to complete a part of the social skills tasks). Unity 3D was selected as the AR development framework, the development of the AR application suite was based on Vuforia AR development framework, which has strong marker-based tracking features and is cross-platform. The assessment tools were the Cognitive Assessment System Second Edition (CAS2) to assess the cognitive measures, Bruininks-Oseretsky Test of Motor Proficiency (BOT-2) to assess fine motor abilities, and Strengths and Difficulties Questionnaire (SDQ) to evaluate social-emotional outcomes. R (4.3.1) and SPSS (29) were used to perform statistical analysis, using paired and independent samples t-tests, Cohen d effect size calculations, and mixed-model ANOVA (repeated-measures comparisons). The platform analytics were visualised using a bespoke teacher dashboard developed in React.js, using a Node.js back-end, and MongoDB data layer.

- **Evaluation Metrics**

The main evaluation measures were: (1) Task Accuracy Rate - the proportion of correctly performed AR module tasks per session; (2) Response Time - the average time spent by the learner when performing the tasks, and it was used as a proxy of cognitive processing efficiency; (3) Retention Rate - the percentage of correctly remembered items on delayed retention tests at one, two, and four weeks post-intervention; (4) Engagement Index - a Secondary measures involved the quality of social interactions rated by teachers and generalisation of skills to home and community settings, as rated by parents. All the metrics were specified and operationalised in advance and listed in a pre-analysis plan to reduce outcome reporting bias.

V. Results and Discussion

Table 2 presents pre- and post-intervention engagement metrics for both the AR intervention and traditional instruction groups. The engagement data in Table 2 show a trend of significant and steady improvement in all indices of engagement measured in the AR intervention group, and significantly higher than the improvements in the traditional instruction group. The increase in on-task time was more than double, or 75 percent, in

the AR group, which was 12.4 minutes per session on task at baseline versus 21.7 minutes at post-intervention, versus a rather less significant increase of 11.8 to 14.9 in the traditional group. The mean scores of student motivation improved by 64.6% and it reached 7.9 out of 10 in the AR group (previously 4.8), which can be attributed to the inherently motivating nature of interactive digital content reported in the reviewed literature, such as Doulah et al. (2023) and Fuentes et al. (2025).

Table 2: Engagement Metrics — Pre and Post Intervention

Metric	Pre-Intervention	Post-Intervention (AR)	% Change
On-Task Time (min/session)	12.4 ± 2.1	21.7 ± 1.8	+75.0%
Student Motivation Score (/10)	4.8 ± 0.9	7.9 ± 0.7	+64.6%
Voluntary Re-engagement Rate	38%	81%	+113.2%
Sessions Completed (/20)	11.2	18.6	+66.1%
Attention Span (min)	7.3 ± 1.5	14.1 ± 1.2	+93.2%

Of particular interest is the 113.2 percent increase in voluntary re-engagement rates- 38 percent to 81 percent, which demonstrates that children in the AR group were much more prone to become engaged in learning activities again after breaks or interruptions. This observation is consistent with the self-determination theory of motivation, according to which, the autonomy-supporting and competence-building characteristics of properly designed AR settings facilitates intrinsic motivation. Of particular importance are the results of the attention span, which have gone up by 7.3 to 14.1 minutes (93.2%), considering that attentional problems constitute a key impairment in all the disability groups included in the sample? The size of these engagement gains (consistently over 60% by measure) indicates that the adaptive design and multisensory delivery of the AR framework were able to overcome the attentional and motivational obstacles that the majority of learning is limited by in children with disabilities.

Table 3 presents skill-domain accuracy scores for both groups at pre- and post-intervention assessment points. Accuracy data in Table 3 show that all the five skill domains had educationally significant increases in the AR intervention group and the post-intervention scores were always higher by 20-30 percentage points in the AR intervention group compared to traditional group. In literacy, AR group scores improved by 41.2% to 78.6% as compared to an improvement of 40.8% to 54.3% in the traditional group -a difference of 24.3 percentage points. The same was evident in numeracy whereby the AR group made an increment of 38.7% to 74.9% compared to the traditional group of 39.1% to 51.2%. The highest AR gains were on motor coordination tasks which increased by 44.5 to 80.3, which is quite remarkable considering that development of motor skills is traditionally a hard task to accomplish by conventional instruction alone and usually necessitates intensive one to one physical instruction.

Table 3: Skill Domain Accuracy — AR vs Traditional Instruction

Skill Domain	Pre AR (%)	Post AR (%)	Pre Trad (%)	Post Trad (%)
Literacy (Word Recognition)	41.2	78.6	40.8	54.3
Numeracy (Basic Operations)	38.7	74.9	39.1	51.2
Motor Coordination Tasks	44.5	80.3	43.9	56.7
Memory Recall Tasks	35.8	72.1	36.2	49.8
Social Interaction Scenarios	39.3	76.4	38.7	52.1

This deficit seems to have been specifically met by the gesture-based interaction design of the Motor Skills Module, which offered real-time visual guidance on trajectories, which learners could perceive and respond to separately. The recall accuracy in AR group improved to 72.1% -almost doubling the original 35.8%- whereas the recall accuracy in the traditional group improved by only 36.2 to 49.8%. This observation supports the dual-

coding theory of memory that postulates that concurrently presented information (visual and auditory) is encoded more profoundly and enduringly than information presented in one mode. The results of social interaction scenarios revealed an increase of 39.3 per cent to 76.4 per cent in the AR group indicating the strength of AR-based social simulation to offer safe, low-stakes practice conditions to develop social scripts.

Table 4: Retention Rates — AR vs Traditional Instruction

Assessment Point	AR Group (%)	Traditional (%)	Difference (%)	Statistical Sig. (p)
Immediate Post-Test	82.3	61.4	+20.9	$p < 0.001$
1-Week Retention	76.8	52.7	+24.1	$p < 0.001$
2-Week Retention	71.2	44.3	+26.9	$p < 0.001$
4-Week Retention	65.9	38.1	+27.8	$p < 0.001$

Table 4 shows the retention data at four assessment intervals and it is evident that there is a significant statistically significant difference in favor of the AR group in all intervals. The AR group immediately retained more (82.3% vs. 61.4% in the AR and traditional groups, respectively) and the difference between the two groups (20.9 percentage points) was significant ($p < 0.001$). This benefit increased with time, not decreased, like with more strongly encoded learning. By the delayed retention assessment at 4 weeks, the AR group was able to remember 65.9 percent of the material learned as compared to 38.1 percent of the material learned by the traditional group - a difference of 27.8

percentage points. This trend is also in line with the better consolidation of multisensory memories as compared to unimodal memories and is corroborated by the results of El Shemy et al. (2024) and Yang et al. (2025). The steadily increasing retention gap indicates that the immersive, context-filled learning experiences provided by AR produces stronger long-term memory cues compared to the much more symbolic and text-based experiences of conventional learning. The significance of all the between-group differences ($p < 0.001$) at all four time points confirms that the observed benefits are not due to chance and the effect sizes (Cohen d 0.88 to 1.34 with the retention intervals) are large and

empirically important. These retention results have important practical implications: a technology that yields lasting learning gains at four weeks follow-up is very important in decreasing the remedial teaching load of special education teachers and making education a better investment.

Rigorous statistical analysis was done on all the primary outcomes. The post-intervention between-group comparisons were performed with the independent samples t-tests with the Welch's correction of the unequal variances; the within-group comparisons were performed with the paired-samples t-tests. Cohen d was used to determine the size of the effect and all tests were done at the 0.05 significance level, with Bonferonni correction to control multiple comparisons. The model of time-by-group interaction in retention outcomes was modeled using mixed-model ANOVA with repeated measures. The findings established that there was statistically significant interaction between time-by-group ($F(3,198) = 47.2, p < 0.001, \text{partial } \eta^2 = 0.42$) indicating that the time-by-group retention trajectory was statistically different across groups as predicted. There was a significant overlap in the sensitivity

analysis results which did not include the sample with missing data, which supports the validity of the results. Disability-based subgroup analyses showed that the effects of AR were consistent and positive in all four subgroups: ASD, dyslexia, ADHD, and mixed disability, but the largest effect sizes were observed in the ASD subgroup - in particular, on social skills and attention outcomes - which aligns with the ASD-focused evidence on this topic reviewed in Doulah et al. (2023) and Mittmann et al.

Table 5 shows that the outcome data (cognitive and motor) show large effect sizes in all five domains measured in the AR intervention group. The working memory scores also rose by 42.1 to 68.4 (Cohen $d = 1.24$), which is also an indication of the high demand the AR-based tasks present when it comes to manipulating and updating the information stored in the memory as interactive sequences. The highest effect size ($d = 1.47$), which ranges between 38.6 and 71.3, was observed in attention and focus, which is in line with the results of Fuentes et al. (2025) reporting that AR environments with adaptive difficulty calibration are better to maintain the attentional engagement in comparison to traditional instructional materials.

Table 5: Cognitive and Motor Skill Outcomes — AR Intervention Group

Cognitive Domain	Pre-Score	Post-Score (AR)	Effect Size (d)	Interpretation
Working Memory	42.1	68.4	1.24	Large effect
Attention & Focus	38.6	71.3	1.47	Large effect
Spatial Reasoning	44.8	73.6	1.31	Large effect
Fine Motor Coordination	47.2	76.8	1.18	Large effect
Emotional Regulation	35.9	62.7	1.09	Large effect

The increase in the spatial reasoning ($d = 1.31$) 44.8 to 73.6 supports the scoping review by Yang et al. (2025) that found AR to be especially useful in developing spatial skills in a mathematics setting. The scores of fine motor coordination improved (47.2 to 76.8 [$d = 1.18$]) indicating that the gesture-recognition feedback system was effective to aid in motor planning and execution. The results of emotional regulation, not a direct instructional goal but measured as a secondary outcome, had a positive difference of 35.9 to 62.7 ($d = 1.09$) to

indicate that the predictable, structured, and positive-reinforcement rich AR environment did lead to improvements in self-regulatory capacity, which has important implications in the management of inclusive classroom behaviour. The effect sizes of all the above are greater than Cohen convention of a large effect ($d > 0.80$), which validates that the AR framework had significant developmental effects on all the cognitive and motor levels of children with learning disabilities.

VI. Conclusion and Future Scope

This research has presented a detailed empirical data of the effectiveness of an AR-based learning model in enhancing engagement, accuracy, retention and cognitive development outcomes in primary school students with learning disabilities. The AR group was found to have significantly better improvements in on-task time (75%), motivation (64.6%), and voluntary re-engagement (113.2) than the traditional instruction group, across 12 weeks of intervention. The accuracy of skill domain scores ranged between 30 and 36 percentage points higher than traditional group in literacy, numeracy, motor coordination, memory and social skill domains. There were greater benefits of retention on the AR group as the weeks went by, with the maximum benefit of 27.8 percentage points at the four-week delayed test ($p < 0.001$). Significant effect sizes ($d = 1.091.47$) were observed in all cognitive and motor domains and the three-layer AR system architecture (including Data, Interaction and Feedback layers) was able to operationalise concepts of personalisation, multisensory learning and adaptive scaffolding in a realistic classroom setting. Challenges in implementation such as cost, training of teachers, technical reliability, sensory design and curriculum integration have been identified and systematically mapped to evidence based mitigation strategies. The implications of the findings of this study have serious consequences at both the educational system and the society. The AR framework provides a scalable and practical mechanism on how to provide differentiated instruction to children with various learning needs in inclusive classroom settings, eliminating the need to rely on one-to-one specialist instruction which often is costly and limited. The reported gains in attention, self-regulation and social interaction have broader developmental implications than just the academic sphere, reinforcing the more general developmental outcomes - such as peer relationship quality, family wellbeing, and long-term employment opportunities - that are highly reliant on early intervention in children with learning disabilities. The findings of the study contribute to the evidence base of the strategic inclusion of AR-

based assistive technologies in the frameworks of national special education and digital learning strategies at the policy level. The cost-barrier results support the argument to have assistive technology hardware in under-resourced schools subsidised by the government, and the teacher training data emphasises the importance of pre-service and in-service professional development curriculum that develops AR competency as an essential part of special education teacher preparation.

A number of significant research directions that should guide future studies are brought out in this study. To establish whether the short-term benefits reported here are sustained, generalised and transferred into quantifiable changes in academic qualification outcomes, longitudinal studies of the effects of AR interventions over a one or more full academic year would be required. Comparative studies comparing AR to other modern assistive technologies - such as AI-based adaptive learning platforms and VR-based immersive interventions - would be useful in shedding some light on the relative superiority of AR to other types of assistive technology. Studies that would specifically focus on under-represented disability groups (such as children with dyscalculia, developmental coordination disorder and complex communication needs) would be able to broaden the applicability of AR models beyond the currently dominant evidence base of ASD. A high-priority methodological requirement is the development and validation of standardised AR outcome measurement frameworks, which would allow the cross-study comparison. Lastly, health economics research assessing the cost-effectiveness of AR interventions compared to conventional specialist support would be the policy-relevant evidence to support the infrastructure investment necessary to implement on a large scale. The addition of AI-based personalisation algorithms, biometric learner tracking in real-time and wearable AR interfaces to the next-generation platforms is a promising future that, when implemented in a responsible and inclusive manner, can radically transform the educational experience of children with learning disabilities all over the world.

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