Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-025-05292-y OPEN

Effects of STEM learning on students with autism spectrum disorder and students with intellectual disability: a systematic review and meta-analysis

Fang Da[1,2], Ying Ma[1], Minjie Ma[3], Jieyu Mao[1,4], Zijiang Weng[1,5], Chao Yang[2] & Tingzhao Wang[1✉]

Although science, technology, engineering and mathematics (STEM) education is known to benefit students with autism spectrum disorder (ASD) and students with intellectual disability (ID), its efficacy has not been fully evaluated. This systematic review and meta-analysis examined the (1) overall intervention, maintenance and generalisation effect sizes of STEM learning; (2) effectiveness of intervention methods; and (3) influence of moderating variables (age, sex, disability type, intervention setting, interventionist and intervention duration.) Based on a Web of Science search, 40 studies published between January 2010 and July 2023 were included. This study involves two distinct groups: students with ID and students with ASD. Within the ASD group, participants were subdivided into two subgroups based on comorbid ID status: ASD-ID (with comorbid ID) and ASD-no ID (without ID). STEM learning had strong overall intervention and maintenance effects on students with ID and ASD. Disability type had a moderating effect on STEM learning outcomes, students with ASD-ID having more severe impairments compared to students with ASD-no ID and those with ID alone. This study has summarised interventions suitable for different fields and types of disabilities; educators should further optimise interventions that are proven effective. Future research should continue to focus on factors affecting the STEM learning outcomes of students with ASD and students with ID to help them improve their learning experiences, better understand the world and participate in social activities.

[1] Faculty of Education, Shaanxi Normal University, Xi'an, Shaanxi, PR China. [2] Xi'an Qizhi School, Xi'an, Shaanxi, PR China. [3] Xi'an Mangya School, Xi'an, Shaanxi, PR China. [4] Hangzhou Yanglingzi School, Hangzhou, Zhejiang, PR China. [5] Chengdu Tonghui (International) School, Chengdu, Sichuan, PR China. ✉email: wangtingzhao@snnu.edu.cn

Introduction

Intellectual Disability (ID) and Autism Spectrum Disorder (ASD)[1] are among the most prevalent developmental disorders (Srivastava and Schwartz, 2014). Collectively, these two disorders affect 3–5% of the population, posing significant social problems across all countries (Bitsko et al., 2022). Approximately 65% of children diagnosed with ASD also have ID (Strnadová et al., 2016; Dykens and Lense, 2011). During the last decade, the growing trend of educating children with ASD and ID in inclusive classrooms has led to an increased emphasis on their academic performance and instructional approaches (Alresheed et al., 2018; Selanikyo et al., 2017). Students with these conditions often face challenges in executive functions (EF) (Roelofs et al., 2015)—higher-order cognitive processes critical for adapting to new environments (Elliott, 2003)—such as working memory deficits impairing knowledge application and limited cognitive flexibility hindering instructional adaptation (Corbett et al., 2009; Hill, 2004). These EF impairments significantly impact academic performance (Benallie et al., 2021; Matson et al., 2009) and pose challenges to school adaptation. Enriching the learning content, establishing diversified educational models and enhancing educational effectiveness for students with ASD and students with ID is crucial to ensuring educational equity in special education (Di Blasi et al., 2023). The integration of science, technology, engineering and mathematics (STEM) into K-12 and higher education curricula requires the involvement of one or more of these four disciplines (National Academy of Engineering and National Research Council, 2002), emphasising a student-centred approach to foster students' innovative thinking and scientific spirit (Breiner et al., 2012). It provides students with ASD and students with ID the opportunity to understand the world more authentically (Basham et al., 2010). These findings have important implications for special education teaching and rehabilitation training. Therefore, educators need to ask, 'What can STEM learning bring to students with ASD and students with ID and how effective is it?' This study carried out a meta-analysis to answer this question.

The Benefits of STEM learning for students with ASD and students with ID. First, the structured learning environment provided by STEM aligns with the cognitive characteristics of students with ASD and students with ID (Schreffler et al., 2019). For example, offering specific topics, clear objectives and learning content matched to students' abilities meets the learning preferences of these students regarding predictability and reduced uncertainty (Murthi et al., 2024). The interdisciplinary nature of STEM allows these students to explore and learn in various ways and better understand complex concepts (Hwang and Taylor, 2016). Such authentic experiences promote students' participation in learning rather than acquiring knowledge through isolated facts. Spooner et al. (2011) highlight the significance of discovery-based learning and naturalistic enquiry as critical components of STEM learning for students with ASD and students with ID. Engaging in enquiry behaviour and problem-solving encourages students to think actively through prediction, reasoning and questioning.

Furthermore, STEM learning also meets the social and emotional requirements of students with ASD and students with ID (Hughes et al., 2022), enhancing their emotional expression, emotional interpretation and conflict mediation skills (Hughes et al., 2022) and strengthening their academic self-concept (Ozkan and Kettler, 2022). Lastly, STEM learning has expanded employment opportunities for students with ASD and students with ID. STEM education involves all learners (National Research Council et al., 2000) and its interdisciplinary practices enable students to acquire transferable skills, which are crucial for their employment preparation (Nachman et al., 2024; Zollman, 2012).

The practical application of intervention methods in STEM learning on students with ASD and students with ID. Over the past few years, research on STEM education for students with ASD and students with ID has largely been related to the application of teaching methods. Research indicates that a hands-on, applied and authentic approach to STEM instruction could benefit ASD or ID students (Israel et al., 2013). STEM educators have adopted innovative and engaging methods with practical implications in various real-world contexts. For example, to address students' EF deficits, educators have adopted structured teaching strategies. By transforming complex STEM skills into actionable steps through the 'problem-posing–hypothesis-testing–conclusion-evaluation' process (Wright et al., 2020), the cognitive load on ASD students is reduced.

Meanwhile, explicit instruction and systematic teaching procedures can assist ID students in breaking down tasks and by utilising tools such as visual flowcharts and operational checklists, the burden on working memory is alleviated, enabling them to effectively master STEM skills (Taylor, 2018). In addition, some researchers have adopted cooperative learning strategies to meet these students' social development needs. For example, robotics projects based on peer-mediated groups positively impact the STEM learning motivation of children are ASD, ID and other disabilities (Lindsay et al., 2019) and could promote peer relationships. Educators can employ a single intervention method, such as using prompts and video demonstrations when teaching mathematics and science to students with ASD (Hart and Whalon, 2008). Additionally, practitioners can also combine explicit instruction, time delay and technology-based interventions (Ehsan et al., 2018; Wright et al., 2020).

Research gaps. Although previous research has emphasised STEM learning benefits, students with ASD and students with ID still face challenges. Owing to struggles in both comprehension and articulation of information, as well as issues with executive function, students require adaptations when receiving instruction (Fleury et al., 2014). Notably, the heterogeneity among students with ASD, such as whether they have co-occurring ID, can lead to varying learning outcomes (Verté et al., 2006). However, some researchers focus only on 'pure autism' or idiopathic, primary, or non-syndromic autism without ID, leading to insufficient practice and research for individuals with ASD and co-occurring ID (Amaral et al., 2011; Vivanti et al., 2013). Therefore, the effectiveness of teaching STEM to students with different types of disabilities as well as the maintenance and generalisation of interventions need to be evaluated to understand their long-term effects (Iatraki and Soulis, 2021). Additionally, Knight et al. (2013a; 2013b) noted that, compared to areas like literacy, the absence of research-based interventions results in practitioners lacking confidence in teaching science and mathematics to students with ASD and students with ID, leading to a gap in the field of engineering education. To assist educators in better teaching STEM to this population, it is essential to compile applicable intervention methods and teaching strategies (Ayeni et al., 2024). Given the diverse nature of students with ASD and students with ID, many studies have focused on single-case designs (SCDs) to assess the effects of STEM learning. The number of meta-analyses of such studies is limited and it remains unclear which variables affect the effectiveness of STEM interventions. Therefore, this study assesses single-case studies of STEM learning that involve students with ID and ASD, with the ASD group further divided into two subgroups based on whether there is comorbid ID. Therefore, the disability types included ID, ASD without ID (ASD-no ID) and ASD with ID (ASD-ID) to enable a holistic evaluation of individual study effects and the connections between distinct study attributes and their outcomes. Subsequently, the research questions (RQs) were as follows:

(1) What are the overall interventions, maintenance and generalisation effects of STEM learning on students of ASD and ID?
(2) What are the effective intervention methods available for STEM teaching for students with ASD and students with ID, and what impact do they have on learning outcomes?
(3) What are the potential moderating effects of participant and intervention process characteristics on STEM learning outcomes for students with ASD and students with ID?

Methods

Data source. This study investigates SCD studies in interventions for students with ASD and students with ID. This method is ideal for establishing causal relationships in behavioural interventions through within-subject comparisons (Horner et al., 2005; Wolery and Dunlap, 2001). Nonparametric tests in SCDs can be used for meta-analysis of intervention measures (Parker and Vannest, 2009). Guided by the PRISMA-ScR checklist (Page et al., 2021), we made specific adaptations for SCDs, especially regarding standardised effect size calculations and moderator analyses of intervention processes and participant characteristics. These steps enhanced methodological transparency and result credibility in our single-case meta-analysis. The procedure involved:

(a) formulating the RQs following the population, exposure, comparison, outcome and time format;
(b) identifying relevant search terms and data sources;
(c) establishing study eligibility criteria that included inclusion and exclusion stipulations and
(d) performing a data extraction and analysis using the selected studies.

The protocol was registered in the International Prospective Register of Systematic Review Protocols (PROSPERO number: CRD42024559772). Studies were searched for and obtained from the Web of Science (WOS) database.

Search strategy. This study used the WOS core collection as the data source. Journals here are filtered by impact factors and peer reviews, aligning with the study's focus on high-quality single-case experimental design literature. The search strategy involved: First, three keyword groups '(ID* OR autism*)' (target population), '(STEM OR STEAM)' (domain) and '(learning)' (context)—were combined using Boolean operators (AND), yielding 134 initial studies. Second, we expanded and refined applied semantics. STEM was decomposed into subfields 'Science*', 'Technology*', 'Engineer*', 'Math*' and terms such as 'STEM education' and 'STEAM education' were added. Educational context keywords were expanded to include synonyms like 'instruction'. By setting the publication date from January 1, 2010, to July 31, 2023 and selecting articles, we obtained 1225 studies. Additionally, a reference search was conducted for review articles relevant to the topic, adding five articles totalling 1230.

Eligibility criteria. Articles were included if they (Fig. 1)

(a) were published in English in peer-reviewed articles;
(b) had an experimental design;
(c) had a single-case research design;
(d) had participants diagnosed with ASD or who received special education classification for autism (i.e. ASD, pervasive developmental disorder, Asperger's syndrome) or ID (i.e. mental retardation; Prader–Willi, Down's, Williams, or Rett syndromes).
(e) had participants aged five to 22 years within the K12 educational system, including those enroled in public or private schools (i.e. elementary, middle, or high school, or transition programmes funded by schools), with the oldest age (22 years) being for students in transition programmes funded by schools or the government;
(f) focused on at least one STEM-related skill or content as a dependent variable (including research that investigated comprehension skills or vocabulary within a STEM field, e.g. understanding scientific texts).
(g) included specific RQs, research methods, detailed intervention processes, systematic data collection and analysis, conclusions and
(h) provided adequate information to calculate the effect sizes.

Data extraction and descriptive coding

Independent variables. In this study, the independent variable was a STEM teaching intervention method (Table 1). Based on the screening results, this study coded this using task analysis, which used self-monitoring checklists and general terms for enquiry-based tasks. The coding results were as follows: computer-assisted instruction (CAI), systematic instruction combined with other strategies, simultaneous prompting (SP), video prompting (VP), explicit instruction combined with other strategies, modified schema-based instruction, schema-based instruction, video modelling (VM), video self-modelling (VSM), constant time delay, cognitive and metacognitive and virtual abstract instructional sequence (VA).

Dependent variables. First, this study categorised STEM intervention goals into four domains: science, technology, mathematics and STEM interdisciplinary areas (Table 1). Due to the absence of relevant studies in the engineering domain, variables related to the engineering field were excluded from the analysis.

Second, this study classified STEM intervention goals into five categories:

(1) science ideas and core knowledge,
(2) science enquiry skills,
(3) computer programming skills,
(4) mathematics problem-solving skills and
(5) STEM skills.

Prior research has classified understanding of science texts (Williams et al., 2009), science vocabulary (Jimenez et al., 2009), science content knowledge (Knight et al., 2012) and other skills as science concepts and core knowledge within the science field. Science enquiry involves hands-on practice and problem-solving skills (National Research Council, 1996). Therefore, this study categorised scientific content and problem-solving as science enquiry skills. As computer science and technology include computer and coding programming (Karp and Maloney, 2013), this study included programming skills in the technology field. Mathematics knowledge comprises conceptual understanding and procedural skills (Rittle-Johnson, 2017), where conceptual understanding describes students' comprehension of the underlying mathematical principles or relationships within the learned concepts. Procedural understanding or skills pertain to the methodical undertaking of projected procedures and accomplishing the essential steps for computation (Rittle-Johnson and Schneider, 2014). Hence, this study involved measuring ideas and

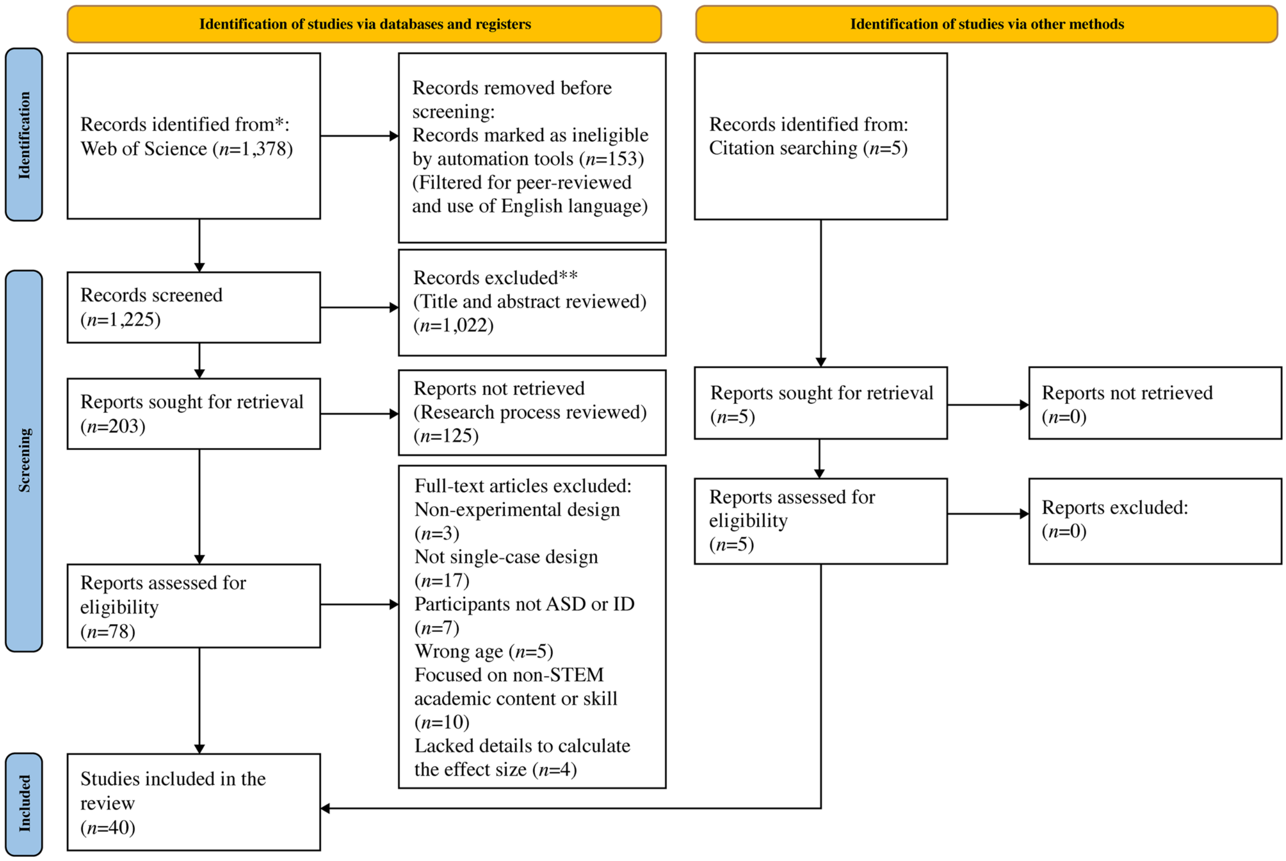

Fig. 1 This study's flow diagram based on PRISMA 2020. *When feasible, this study reported the number of records identified from each database or register searched (rather than the total number across all databases or registers.) **If automation tools were used, this study indicated how many records were excluded by a human and automation tool, respectively (Page et al., 2021).

Table 1 Examples of variables.

Name	Type	Operational Definition
STEM teaching intervention methods	Independent variables	Methods used in implementing STEM teaching for students with ASD and students with ID (e.g. CAI, VM/VSM, VP).
STEM intervention goals	Dependent variables	The intervention goals in the four STEM domains are classified into five categories: science ideas and core knowledge, science enquiry skills, computer programming skills, mathematics problem-solving skills and STEM skills.
Participants' characteristics and intervention processes	Moderating variables	Participants' characteristics included sex, age and disability type. Intervention processes included the interventionists, settings and duration.

STEM science, technology, engineering and mathematics, *CAI* computer-assisted instruction, *VM/VSM* video modelling/video self-modelling, *VP* video prompting.

identifying geometric shapes as mathematical concepts and core knowledge skills and categorised price comparison, addition, subtraction, fractions and other calculation-related problem-solving abilities as computational problem-solving skills (Jitendra et al., 2016). These studies refer to a collective term for skills involving interdisciplinary knowledge in science, technology and mathematics (National Science Foundation: Division of Science Resources Statistics, 2004).

Moderating variables. First, participants' characteristics included sex, age and disability type (Table 1). The participants were students in public or private schools (i.e. elementary, middle, high schools, or transition programmes funded by schools and the government.) Our study focuses on K-12 students (ages 5–22), including those in transition programmes (19+), as mandated by the U.S. Individuals with Disabilities Education Act requiring special education support through Individualized Education Programmes (IEPs). Extended schooling under IEPs accommodates diverse cognitive needs, with interventions primarily within K-12. Age was divided into the following groups: 5–6 years (early childhood), 7–12 years (childhood), 13–18 years (adolescence) and 19–22 years (adulthood). The participants included ID and ASD, with the ASD group further divided into two subgroups based on whether there is comorbid ID. Therefore, the disability types included ID, ASD without ID (ASD-no ID) and ASD with ID (ASD-ID).

Second, the intervention processes included the interventionists, settings and duration. Intervention frequency was not a moderating variable because of differences across STEM areas. Interventionists referred to personnel who implemented the intervention processes, including special education and general teachers, parents, professionals and multi-person collaborations. The intervention settings included special education classrooms, inclusive and general classrooms, resource rooms and centres and homes (refers explicitly to the use of summer vacation, afterschool hours, or other free time by students in public or private schools to receive interventions in a home setting), other locations (e.g. libraries and therapy rooms) and common school areas.

Quality rating of the studies. This study used What Works Clearinghouse design standards and Reichow et al.'s (2008) evaluation criteria to examine the methodological rigour and overall quality of the included studies, the robustness of evidence for specific interventions and whether they qualified as evidence-based practices for individuals with ASD and ID. This approach evaluated the studies based on 12 quality indicators comprising six primary factors (participant characteristics, independent variables, baseline conditions, dependent variables, visual analysis and experimental controls) and six secondary factors (inter-observer agreement [IOA], kappa, blind raters, fidelity, follow-up conditions and social validity.)

The studies were evaluated using the primary quality indicators and categorised as 'high', 'acceptable', or 'unacceptable'. Then, this study considered the presence of the secondary quality indicators, with the studies being classified based on whether there was 'evidence' or 'no evidence' for these aspects. Based on WWC standards and Reichow et al.'s (2008) evaluation criteria, a study was categorised as strongly rigorous if it achieved high scores for all primary factors and presented evidence of three or more secondary quality factors. Adequate rigour was assigned to a study if it scored highly on a minimum of four of the six primary factors, had no unacceptable ratings and demonstrated at least two secondary quality factors. Weak rigour was assigned if a study scored highly on fewer than four primary quality factors or received unacceptable ratings. Among the 40 included studies, 17, 21 and 2 had strong, adequate and weak rigour, respectively. Rockwell et al. (2011) and Kasap and Ergenekon (2017) were downgraded due to insufficient high-scoring core criteria (2/6, 3/6) and failure to meet the strong rigour (≥4 high-scoring criteria). Despite limited explanatory power, these studies remain representative in the field. To ensure comprehensive evidence, all 40 studies were included in the final analysis.

Single-case risk of bias tool. This study used the single-case risk of bias (SCRoB) tool to identify potential bias sources that could result in overestimation or underestimation of intervention effects. It codes for nine categories (Reichow et al., 2018): sequence generation, participant selection, blinding participants and personnel, procedural fidelity, blinding outcome assessors, selective outcome reporting, dependent variable reliability, data sampling and other sources of potential bias. Each study was reviewed and categorised as having a high, low, or unclear risk of bias under four broad categories: selection, performance, detection and other sources. Two primary authors independently evaluated all studies through dual-blind coding based on operational definitions of SCRoB's nine domains and criteria for risk classification. A pilot assessment of 5 studies ensured criterion alignment prior to formal evaluation. Discrepancies were resolved through consensus discussions, with unresolved cases arbitrated by a third author.

Coding reliability. This study reviewed and assigned codes to each included study in the following areas: (a) participant demographics, including sex, age and grade level; (b) intervention process details (e.g. setting, intervention and duration); (c) STEM-related skills; (d) intervention methodology; (e) research design; (f) procedural fidelity; (g) efficacy; and (h) social validity. Unclear, missing, or unreported information in each study was identified and coded. The first, second and third authors independently assessed all the randomly selected studies (100%). A total of 560 items (14 coding items across 40 studies) were used to code the variables for each study. The authors determined inter-rater reliability by comparing the agreements and disagreements between the coders. The process entailed dividing the exact agreements by the total count of agreements and disagreements and multiplying the result by 100. Prior to formal coding, the researchers validated the coding framework through pilot coding of 5 preliminary studies (pre-test IOA = 91.4%). The final coding phase achieved an overall IOA of 93.57%, ranging from 90.04% to 97.1%. All discrepancies were resolved using a consensus-based approach, where the three coders discussed and reconciled differences until unanimous agreement was reached for subsequent analyses (Supplementary Tables S1 and S2).

Statistical analyses. A nonoverlapping Tau-U calculator (Parker et al., 2011) was used to compute each study's effect size calculations and confidence interval (CI) estimates. Tau and Ta-U have stronger statistical power than other nonoverlapping indices and could control for the influence of baseline and intervention period trends on the results. The Tau and Ta-U values ranged from −1 to 1, with values of 0.93> indicating strong effectiveness, 0.82–0.92 indicating high effectiveness, 0.66–0.81 indicating moderate effectiveness, 0.48–0.65 indicating weak effectiveness and <0.47 indicating no effectiveness. Based on existing meta-analyses, the overall generalisation and maintenance effect sizes used a 95% CI (Hong et al., 2016; Pan et al., 2023). This study independently coded the included studies and calculated the effect sizes; the Tau and Ta-U consistencies were 91.57%.

Most meta-analyses exclude SCDs (Allison and Gorman, 1993). A meta-analysis of 375 studies examined the outcomes of psychological therapy. It only included studies with at least one treatment group compared to a control group (Smith and Glass, 1977). Single-case studies are often excluded from meta-analyses, although they show meaningful variations. Therefore, this study searched the literature and summarised the methods for meta-analyses applicable to SCDs to ensure statistical significance. Schenker and Gentleman (2001) pointed out that judging the significance of differences by examining the overlap of 95% confidence intervals (CIs) leads to an overly low Type I error rate. Knol et al. (2011) validated this conclusion, finding that the actual error rate of the overlap test using 95% CIs was only 0.0056, far below the conventionally expected 0.05. Payton et al. (2003) further demonstrated that using 95% CIs yields overly conservative results and when standard errors are approximately equal, closer to 84% size for the intervals would give an approximate $\alpha = 0.05$ test. Subsequent studies, such as Ninci et al. (2020), adopted 95% CIs to evaluate main effects in a meta-analysis of single-case research on embedding interests for individuals with ASD, while using 83.4% CIs to interpret non-overlapping effects in forest plots for moderator analyses. Huang et al. (2023) and Tang et al. (2023), in single-case meta-analyses, utilised 85% CIs to balance statistical rigour and sensitivity. Building on these approaches, this study retains 95% CIs for overall effect evaluations and employs 85% CIs for nonoverlapping tests of moderator variables, thereby balancing Type I error control with the nonparametric nature of single-case data. As the Tau-U values had nonparametric properties, to ensure the statistical significance of the results, a lack of overlap in the 85% CI of the moderating variables indicated a difference. This study used a one-way analysis of variance and the Kruskal–Wallis test (Kruskal and Wallis, 1952) using the SPSS software. Following this, inter-group differences were integrated to interpret the moderating effects of variables.

Results

Study characteristics. This meta-analysis included 40 studies, with 138 intervention effect sizes, 46 generalisation effect sizes and 103 maintenance effect sizes. Regarding the experimental design paradigms, all 40 studies used SCD. These included multiple probes across participants; behaviours, skills and units ($n = 30$); multiple baselines across participants ($n = 5$); an alternating treatment design ($n = 1$); a changing criterion design ($n = 1$); and a reversal design ($n = 3$). Concerning the reliability and validity of the studies, 38 reported an IOA score above 85%, 37 reported a fidelity of intervention implementation score above 90% and 28 reported a high social validity of the research through feedback from participants and stakeholders (Supplementary Table S1).

Overall effect sizes. The overall intervention effect size (Table 2) for the 40 studies was 0.928, indicating an impact. Thirty studies reported extremely robust results. Notably, the effect size of the 18 studies was one. In addition, four studies had high effects, four had medium effects, one had a weak effect and one had no effect. All 40 included studies contained intervention effect data and were included in subsequent analyses, with no studies excluded.

Regarding the maintenance effect size (Table 2), the overall score across 29 studies was 0.901, indicating a strong overall effect. Specifically, 23 studies demonstrated strong effects, with 20 studies having a maintenance effect score of one, two (highly effective), three (moderately effective) and one (showing no effect).

Regarding the generalisation effect size (Table 2), the score across 14 studies was 0.787, suggesting a medium overall effect. Notably, five studies displayed strong effects, two had an effect value of one, five showed moderate effects, five demonstrated weak effects and one showed no effect. In summary, STEM learning for students with ID and ASD showed high overall intervention effects, highly effective maintenance effects and moderate generalisation effects (Table 2).

Among STEM disciplines (Fig. 2), mathematics studies had the highest representation, followed by science. In contrast, technology and interdisciplinary studies had less representation, whereas engineering had no representation. The STEM domains had strong to extremely strong intervention effects, with the technology domain showing the highest score (1), followed by scientific enquiry skills (strong: 0.98), solving computation-related problems (strong: 0.959), mathematics (0.95), mathematical concepts and core knowledge (high: 0.903) and science concepts and core knowledge (high: 0.858). The interdisciplinary STEM domain had a high intervention effect (0.878).

Table 2 Overall effect sizes.

	K	TAU	*P*	CI 95%
Intervention	138	0.928	<0.001	[0.897, 0.959]
Generalisation	47	0.787	<0.001	[0.706, 0.869]
Maintenance	92	0.901	<0.001	[0.830, 0.971]

CI confidence interval, *K* number of effect sizes.

Effect size analysis of the STEM intervention methods. The meta-analysis included 138 independent intervention effect sizes. Table 3 shows that the effect sizes of STEM intervention methods ranged from medium to extraordinarily strong. Specifically, studies adopting enquiry-based task analyses in the science domain showed a robust effect score (0.982) and no overlap in the 85% CI compared with the CAI, SP and systematic teaching intervention methods. In the technology domain, the combined use of VP and explicit teaching demonstrated the most significant effect (effect score of one). Similarly, in mathematics, studies combining explicit instruction with other strategies and cognitive and metacognitive approaches showed the most substantial impact (effect score of one). Notably, the effect size of systematic teaching did not overlap with that of the VM or VSM approaches (85% CI). Finally, in interdisciplinary STEM areas, SP prompting had a substantial effect size (0.878).

Some intervention methods show slightly different effects among students with different types of disabilities (Fig. 3). Explicit instruction, MSBI/SBI and VM/VSM have been used in students with the three types of disabilities, producing extremely strong intervention effects. Task analysis demonstrates extremely strong intervention effects in ASD-no ID and ID students. The use of CAI in students with ASD-no ID shows extremely strong intervention effects (effect size of 1), but the effectiveness is moderate in students with ASD-ID (effect size of 0.688). VP demonstrates extremely strong effect sizes in both ASD-no ID and ID students (0.973; 0.980), but the intervention effect is moderate in students with ASD-ID (effect size of 0.708).

Effect analysis of the moderating variables. The moderating variables comprised the participants' characteristics and STEM intervention processes (Fig. 4). Due to the absence of information from certain studies, the overall number of moderating variables fell short of the total independent effect sizes.

Participants' characteristics. The meta-analysis results (Fig. 4) revealed that sex did not affect STEM intervention outcomes; over half of the participants were male. Overall, the interventions were effective, with a particularly strong effect on females. Interventions were effective for those aged 5–6, 13–18 and 19 years and older and highly effective for those aged seven to 12. There were no substantial differences in the effectiveness among the different age groups. The three disability types showed distinct differences, as evidenced by the nonoverlapping 85% CI and *p*-value (0.002) in the Kruskal–Wallis test. This review suggested that the disability type moderated the efficacy of STEM interventions. The inter-group comparison results showed differences between ID and ASD-ID ($p = 0.026$) and between ASD-no ID and ASD-ID ($p < 0.001$). The science domain showed no overlap in the 85% CI between the ASD-no ID and the ASD-ID groups. The interventions were strongly effective for ASD-no ID and ID in mathematics and highly effective in ASD-ID. The technology

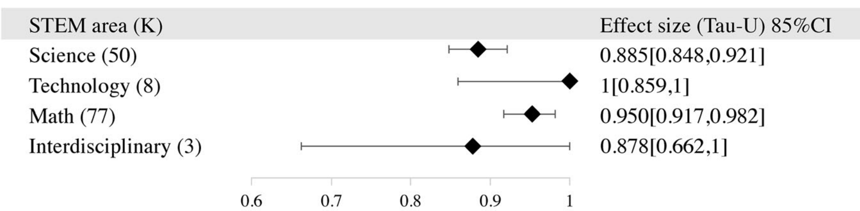

Fig. 2 Forest plot of intervention efficacy in the STEM domains. CI confidence interval, *K* number of effect sizes.

Table 3 Effect sizes of the science, technology, engineering and mathematical intervention methods.

Intervention method	Science			Technology			Mathematics			Interdisciplinary		
	K	TAU	85% CI	*K*	TAU	85% CI	*K*	TAU	85% CI	*K*	TAU	85% CI
Task analysis	17	0.982	[0.971, 0.993]	-	-	-	-	-	-	-	-	-
CAI	10	0.816	[0.692, 0.940]	-	-	-	-	-	-	-	-	-
SP	7	0.874	[0.820, 0.928]	-	-	-	-	-	-	3	0.878	[0.662, 1]
Systematic instruction	16	0.832	[0.764, 0.900]	-	-	-	10	0.872	[0.815, 0.928]	-	-	-
VP	-	-	-	3	1	[0.788, 1]	14	0.857	[0.679, 1.036]	-	-	-
Explicit instruction	-	-	-	5	1	[0.816, 1]	3	1	[0.846, 1]	-	-	-
MSBI/SBI	-	-	-	-	-	-	26	0.990	[0.980, 1]	-	-	-
VM/VSM	-	-	-	-	-	-	17	0.993	[0.987, 0.999]	-	-	-
Cognitive and meta-cognitive	-	-	-	-	-	-	3	1	[0.718, 1]	-	-	-
VA	-	-	-	-	-	-	4	0.942	[0.691, 1]	-	-	-

CAI computer-assisted instruction, *CI* confidence interval, *MSBI/SBI* modified schema-based instruction/schema-based instruction, *K* number of effect sizes, *STEM* science, technology, engineering and mathematics, *SP* simultaneous prompting, *VM/VSM* video modelling/video self-modelling, *VP* video prompting, *VA* virtual-abstract instructional sequence.

domain showed an effect size of one for all three disability types and only students with ID participated in the interdisciplinary STEM aspect (Table 4).

Setting and interventionist characteristics. The intervention settings, interventionists and intervention duration results (Fig. 4) showed no differences. The classroom and centre (setting) intervention results were effective. In contrast, interventions that occurred in other settings were effective, with no differences between the different intervention settings. About half of the interventionists were professional researchers with an extremely strong effect. Collaborative interventions between special education teachers, general and special education teachers and parents were highly effective; there were no differences among the different interventionists. The intervention duration results demonstrated high to extremely strong effectiveness with no differences.

Risk of bias. Supplementary Table S2 presents the bias risk assessment outcomes for the studies. All included single-case studies demonstrated substantial bias levels for two subcategories: blinding participants and personnel and blinding outcome assessors. This type of bias is common in SCD due to the nature of these studies, which often involve small sample sizes and flexible experimental designs (Reichow et al., 2018). The lack of blinding can introduce performance bias and detection bias, potentially affecting the internal validity of the results. The dependent variable reliability category showed low bias in all studies. For procedural fidelity and selective outcome-reporting categories, 32 of the 40 studies exhibited low bias for procedural fidelity and selective outcome-reporting categories. The other sources of bias showed considerable variability, presenting high, unclear and low bias risks across the studies.

Discussion

Effectiveness of STEM learning. This study analysed the overall intervention, maintenance and generalisation effects of STEM learning on students with ASD and students with ID (RQ1). The results showed that the overall intervention and maintenance effects were extremely strong, which aligned with Wright's (2020) results. None of the included studies demonstrated a high risk of bias in participant sampling, dependent variable reliability, procedural fidelity, or data collection factors. Each factor belonged to the single-case research domain directly associated with contemporary single-case research design standards. However, the generalisation effect was moderate, which could be due to difficulties in the cognitive and EF of individuals with ID and ASD (Gunning et al., 2019). Cognitive flexibility deficits, a core feature of executive dysfunction, may impede cross-situational skill transfer (Benallie et al. 2021). In this study, two interventions—CAI and VSM—demonstrated optimal generalisation efficacy (Tau-U = 1). Multisensory inputs (visual, auditory and tactile) augmented information encoding efficiency by activating distributed neural regions, including the visual cortex and PFC (Shams and Seitz, 2008). Real-time feedback mechanisms (e.g. VSM's self-review and CAI's error correction) combined with task variability prevented rote memorisation. Structured supports (e.g. visual cues and procedural scaffolding) mitigated cognitive flexibility deficits in ASD and ID learners while reducing working memory load (Leung and Zakzanis, 2014). By simulating real-world scenarios (VSM) and embedding lifelike problem-solving (CAI), these methods improve skill transfer through contextual variety. These mechanisms likely underlie the superior generalisation effects observed. Educators need to conduct longitudinal studies to examine the long-term effects of STEM learning and

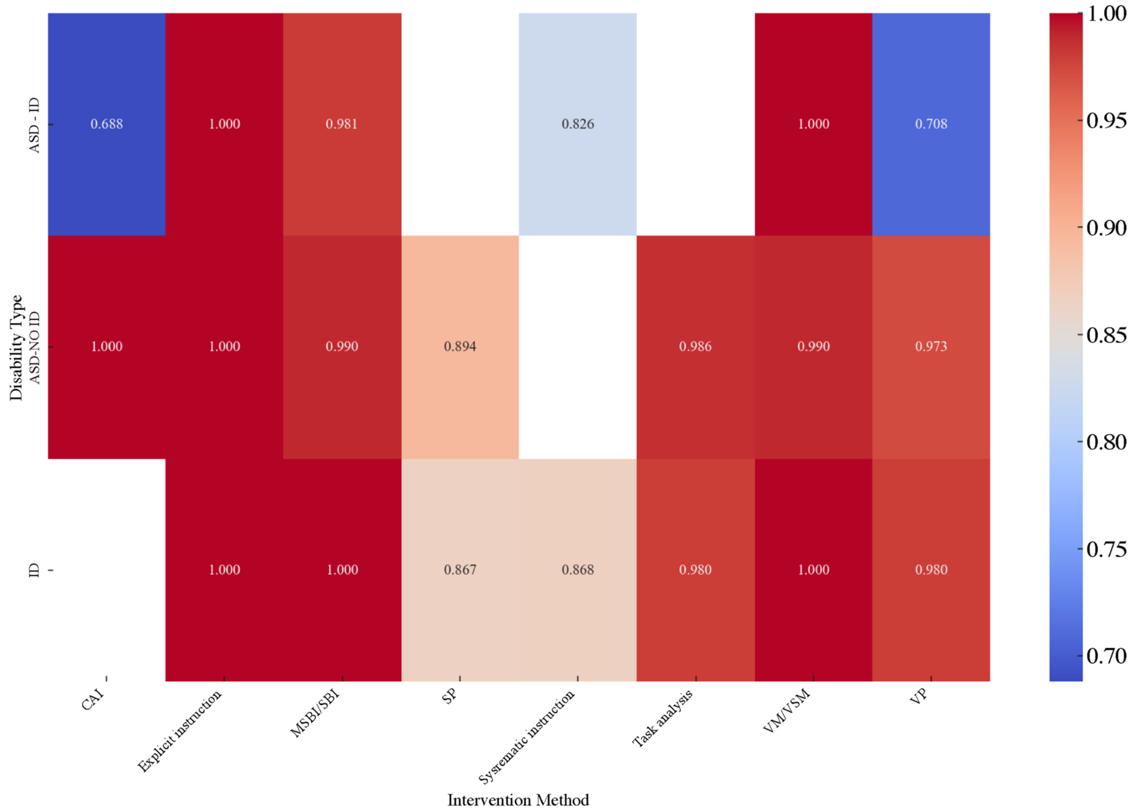

Fig. 3 Heatmap of effect sizes of disability type and intervention methods. ASD autism spectrum disorder, ID intellectual disability, ASD-ID ASD with ID, ASD-no ID ASD without ID.

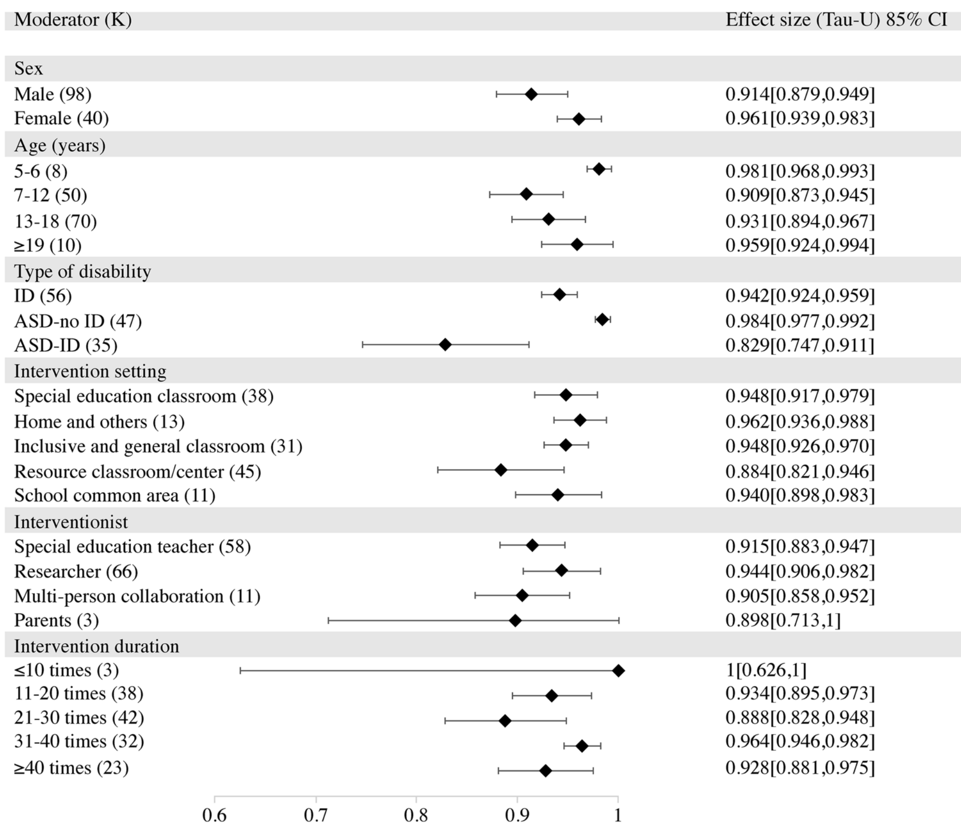

Fig. 4 Forest plot of moderating variables. CI confidence interval, *K* number of effect sizes, ASD autism spectrum disorder, ID intellectual disability, ASD-ID ASD with comorbid ID, ASD-no ID ASD without ID.

Table 4 Effect sizes of disability type.

Disability type	Science			Technology			Mathematics			Interdisciplinary			Sig.
	K	TAU	85%CI	*K*	TAU	85%CI	*K*	TAU	85% CI	*K*	TAU	85% CI	
ID	20	0.927	[0.896, 0.957]	2	1	[0.691, 1]	31	0.954	[0.931, 0.977]	3	0.878	[0.662, 1]	$P = 0.002$
ASD-no ID	14	0.969	[0.948, 0.990]	3	1	[0.796, 1]	30	0.990	[0.983, 0.996]	-	-	-	
ASD-ID	16	0.759	[0.664, 0.854]	3	1	[0.788, 1]	16	0.867	[0.712, 1.023]	-	-	-	

ASD autism spectrum disorder, *ID* intellectual disability, *ASD-ID* ASD comorbid with ID, *ASD-no ID* ASD without ID, *K* number of effect sizes.

continue to explore effective ways to enhance the generalisation skills of ASD and ID students.

Existing meta-analyses demonstrate that STEM interventions for K12 students (non-ASD/ID students) typically exhibit moderate-to-large effect sizes based on parametric measures such as Hedges' g, with interdisciplinary approaches showing significantly greater efficacy than single-discipline interventions (Zhou et al., 2024). Utilising Tau-U nonparametric effect sizes, this study reveals distinct learning outcome patterns in students with ASD and students with ID: the technology had the best effect size, science and interdisciplinary domains had high effect sizes and mathematics had an extremely high effect size. Notably, all studies in the technology domain predominantly employed robotics as instructional tools, demonstrating unique advantages. For instance, Diehl et al. (2012) observed that children with ASD exhibit heightened reliance on robotic platforms due to their repetitive and predictable learning environments, which mitigate social communication barriers. Yuen et al. (2014) further demonstrated that robot-assisted STEM group activities, through structured task decomposition and predictable procedural behaviours, effectively compensate for deficits in executive functioning and working memory, thereby enhancing exploratory behaviours, collaborative skills and programming competencies in ASD learners. Thus, the structured, low-social-pressure pedagogical approaches mediated by robotics appear to align with the cognitive and behavioural profiles of ASD or ID students (Kotsi et al., 2025), addressing learning barriers inherent in conventional settings. However, there are few studies in this field and the robustness of the intervention effect requires further verification. Future efforts should explore integrating multimodal affective recognition and natural language processing technologies (Pérez et al., 2024) to enhance robotic adaptability for ASD and ID learners. Additionally, the engineering domain has not yet generated quantifiable evidence. This disciplinary imbalance suggests that future research should explore engineering practices tailored to students with ASD and students with ID.

Among STEM-related skills, coding skills had the best intervention effect, with an effect size score of one. In addition, the intervention effects on science enquiry and mathematics problem-solving skills were extremely strong. Scientific enquiry helps students solve scientific problems and fosters a scientific spirit. Brigham et al. (2011) and Simpkins et al. (2009) affirm this view by stating that cooperative scientific enquiry activities could enhance students' engagement with learning difficulties and facilitate their conceptual understanding and academic achievement progress. In addition, enquiry-based learning helps cultivate the scientific spirit of students with ID (Al-Ahmadi and Oraif, 2009). In mathematics, developing problem-solving skills can enable students to address calculation-related challenges more effectively (e.g. addition and subtraction, price comparisons and fractions.) Studies have shown that developing and applying problem-solving skills could help students with ID and ASD to understand academic knowledge principles (Jitendra et al., 2016). In addition, Archer and Hughes (2011) believe that problem-solving skills could help students generalise and apply mathematical skills to the real world. These results aligned with the current study and indicated that enquiry and problem-solving skills were the core features of STEM education and effective learning approaches. Based on these findings, we suggest that teachers can design cooperative enquiry activities to not only enhance the interdisciplinary knowledge understanding of students with ASD and students with ID but also cultivate their problem-solving skills and foster a scientific spirit.

Effectiveness of STEM intervention methods

Science domain: interventions using step-process-task enquiry methods. This study reviewed and evaluated the effectiveness of STEM intervention methods (RQ2). Interventions using step-process-task enquiry methods were the most effective. These methods provide students with checklists containing task steps or processes to reduce their cognitive load, better guide them in understanding science content through enquiry activities (Miller, 2012) and enhance their problem-solving, self-determination and communication skills (Wehmeyer et al., 2000). For example, students could use self-monitoring checklists for science enquiry activities (Miller, 2015) and verbally express their steps to complete self-assessments. This study's results indicated that students with moderate ID not only generalised the steps of enquiry-based problem-solving to use in everyday problem-solving situations but also showed improved independence in problem-solving. Therefore, designing task analysis lists is particularly important for the smooth completion of scientific enquiry. In practical teaching, teachers first need to break down activities into operable steps and provide students with judgement options, such as observing whether an experiment is complete and what should follow. This approach helps students better understand what they are currently doing and what tasks they are about to complete, allowing them to progress systematically. Furthermore, instructions should be clear to ensure they do not increase the students' reading load.

Technology domain: VP and explicit instruction integrated with other strategies. The results revealed that the optimal intervention methods were VP and explicit instruction, integrated with other strategies. However, there are only three studies in the technical domain, with limited intervention methods identified and the robustness of these interventions requires further exploration. The VP method breaks down a task or skill into individual steps, where participants watch video demonstrations to complete operational steps, similar to the task analysis nature of STEM activities (Banda and Dogoe, 2011). Wright et al. (2021) used the VP method to teach coding skills to students with ASD, where the teachers pre-recorded example videos and the participants completed tasks on iPads after watching them. This study's results indicated that the VP intervention method helped students with ASD generalise new skills. Although the current study did not track the long-term effects of skill generalisation. Given the differences among students with ASD and students with ID, varying reinforcement frequencies and video types may be necessary to maintain skill stability and generalisation, which should be a key focus of future research. The study's findings offer valuable insights for teachers in STEM instruction. The demand for producing high-quality videos may heighten teachers' technophobia (Knight et al., 2018). To address this, schools can expand video resource libraries by having technical staff and researchers collaborate with special education teachers. They can prepare video models in advance based on students' IEP needs, reducing teachers' technical burden. Also, schools should strengthen technical training for educators, such as AI-assisted video production (generating task scripts of proper length, multimodal conversion with text or images) and video editing skills. VP implementation should integrate evidence-based practices (e.g. gestural cues, verbal prompts, behaviour reinforcement.) Such multimodal interactions improve student engagement and offer actionable STEM teaching frameworks for special educators, ensuring intervention feasibility and sustainability.

Explicit instruction combines direct instruction with scaffolding and feedback from students and teachers (Doabler and Fien, 2013). These instructions could help students with ID acquire self-determination and problem-solving skills related to the STEM curriculum through the coding process (Bers et al., 2014). For example, interventionists could use blocks with images or colours to demonstrate the coding processes to students (e.g. a forward arrow indicating forward movement or a red arrow indicating stopping.) Teachers use visual supports and provide detailed explanations during demonstrations, followed by guided practice for students, asking questions and offering immediate feedback. This method may include allowing students to write simple code under the teacher's guidance and gradually increasing the difficulty. As students gain proficiency with basic coding, support is gradually reduced, allowing students to attempt to write and test code independently. The results showed that this modified constructionist approach has achieved significant results in programming education for students with ID, effectively demonstrating the shift from teacher-led to student-centred learning. Teachers maintain students' learning flow by adjusting the difficulty level, promoting optimal engagement and active participation. Future explicit instruction can expand STEM applications via AI-driven adaptive systems and AR. AI systems analyse learning data in real-time, adjusting task difficulty and offering instant feedback, aligning with the 'fading guidance' principle (Veinott, 2022). AR reduces cognitive load with visual scaffolds, aiding intuitive understanding of abstract concepts (Suzuki et al., 2024). AI-integrated systems auto-detect knowledge gaps and optimise feedback (Guo et al., 2024). Future hybrid models combining explicit instruction with AR simulations for coding practice with AI-generated hints and error reports show promise. These technologies preserve explicit instruction's core advantages and offer new applications, better meeting the needs of students with ASD and students with ID to enhance their STEM learning outcomes.

Mathematics domain: cognitive and meta-cognitive approach and explicit instruction integrated with other strategies. The results showed that the optimal intervention methods integrated cognitive and metacognitive approaches and explicit instructions with other pedagogical approaches. Cognitive and metacognitive tactics assist students in executing physical tasks and cognitive processes (e.g. planning, memorising and self-assessing.) Schaefer Whitby (2013) exemplified this method by implementing the 'Solve it!' programme that provided tailored instructional materials for students with executive function impairments to enhance their attention, memory, sequencing and organisational skills using mathematical word problems. The specific procedure involves the teacher presenting pre-recorded videos to the students, who practice according to the K-N-W-S (Know-Need-How-Strategy) approach. Meanwhile, the teacher moves around to answer questions, provide feedback, correct misunderstandings and manage behaviour. After a period, the students cease watching the videos and independently solve problems using the above method. This structured teaching method has successfully transformed video scaffolding into internal mental tools, which align with the executive function deficits of students with ASD and students with ID. It reduces students' cognitive load and provides a generalisable methodology for students to solve problems independently. In practical teaching, teachers should also be proficient in the methods of producing and using learning materials.

This study's explicit instruction comprised three phases: skill modelling, guided practice and independent skill assessment. This method is similar to Liu et al. (2023), who combined explicit instruction and VM to facilitate students' task analysis on tablet devices, thus elucidating the problem-solving procedure. Meanwhile, if students with ASD and students with ID faced uncertainty during the tasks, the facilitators sequentially provided verbal cues, specific prompts and model demonstrations. This approach was in line with the cognitive traits of ASD students; it eased their load on perceptual reasoning and working memory (Oswald et al., 2016) and facilitated their independent comprehension of measurement concepts. This method embodies the integration of structured teaching and personalised learning. AR technology vividly demonstrates the process of solving mathematical problems, including analysing the problem, demonstrating solution steps, deriving the final answer and enhancing students' learning experience. As students master the strategies, teachers gradually reduce guidance, allowing students to attempt to solve problems independently, promoting the generalisation and maintenance of skills. This approach requires teachers to be proficient in the use of digital technology and learn to create rich, interactive teaching scenarios that make abstract concepts more intuitive and understandable. In addition, teachers can also utilise intelligent teaching systems to provide personalised resources and feedback based on students' progress and needs, thereby enhancing teaching effectiveness.

Interdisciplinary domain: cooperative learning combined with SP. Only one study combined a cooperative learning strategy with the SP procedure to instruct students with moderate ID on STEM interdisciplinary content and chained tasks. The SP method simultaneously presents attention and controlling prompts to determine whether students have mastered the target skill. Heinrich et al. (2016) focused on using technological interventions to execute discrete tasks, including gaining knowledge about online publishing and sequential tasks (e.g. Internet searches). The special education teacher provided students with a folder containing their daily assignments, including worksheets for chained tasks and index cards for discrete tasks. When teaching a discrete skill, the instructor presented an attention cue, waited for the students' response and then presented the task directions, followed by a controlling prompt, similar to a verbal model. Aykut et al. (2012) suggested that the SP procedure was a brief yet effective instructional strategy to maintain students' attention and ensure more efficient mastery of STEM skills. In addition to academic skills, interdisciplinary learning content can extend to the humanities. Future attention can also be given to developing social domains, such as cooperation, communication, respect for others' ideas and other social skills. These skills are crucial for students with ASD and students with ID in terms of social adaptation and relationship building. In the interdisciplinary field, educators can explore other interdisciplinary approaches to integrate knowledge and skills from different subjects into teaching, providing a more comprehensive learning experience for those individuals. Moreover, educators can also try to combine peer cooperation with other teaching strategies to enhance students' social interaction and collaboration skills. When students collaborate independently, teachers should promptly reinforce positive behaviours, teach them to express their needs correctly using language and use appropriate behaviours to help peers and initiate and maintain conversations.

The results indicate that explicit instruction, MSBI/SBI and VM/VSM demonstrate extremely strong application effects across the three types of disabilities and task analysis is suitable for students with ASD and students with ID. Some intervention methods demonstrate varying effects on students with different types of disabilities. For example, CAI has different performances, possibly because students with ASD may have a stronger response to visual media, making CAI a promising teaching method (Sansosti et al., 2015). Compared to students with only ASD, students with ASD-ID typically exhibit more pronounced impairments in attention, visual perception and EF (Lin et al., 2024), which may affect the effectiveness of CAI. The intervention effects of VP in students with ASD-no ID and ID can reach a very high level, but the effects in students with ASD-ID are moderate.

Similarly, Video-Based Intervention (VBI) methods like VM/VSM can achieve extremely high levels of intervention for students with all three types of disabilities. This outcome may be because VP is often used as a direct prompting tool, playing videos of specific behaviours to guide learners to imitate them, focusing more on prompting and guidance (Park et al., 2019). Subsequently, VM/VSM is a more comprehensive learning strategy, emphasising the learning process (Delano, 2007). VM not only demonstrates behaviours but also includes learning time. Video models can be peers, learners, or adults, helping learners better understand and practice target behaviours (Stierle et al., 2023). Studies have demonstrated that when intervening with students with ASD and students with ID, using VM results in fewer errors in target skills, better generalisation, easier transfer to new environments and longer-lasting behaviour compared to VP (Thomas et al., 2020). The effectiveness of STEM intervention methods varies due to the diversity of disabilities. The cognitive characteristics and learning needs are different, especially for students with ASD-ID who face the challenges of both types of disorders. Given this, in future STEM teaching, educators should deeply understand the individual characteristics and learning needs of each student, choose intervention methods that match them and further promote and optimise the better-performing interventions to seek greater teaching benefits.

In addition, peer collaboration might increase students' social contact across various activities and inclusive settings and provide them with heightened social support behaviours, broader friendship networks and more enduring peer relationships (Kennedy et al., 1997). However, owing to the limited number of available studies, the resilience of the intervention examined in this study requires further validation.

Impact of the moderating variables on STEM learning effectiveness. The RQ3 study amalgamated the overlapping CIs with Kruskal–Wallis test results to probe the effects of moderating variables (sex, age, type of disability, intervention settings, interventionists and intervention duration) on STEM education.

Disability type. Overall, this study found that students with ASD-ID were likely to encounter increased difficulty in their educational pursuits, which might have contributed to the variations in intervention levels among the three disability types. The intervention effect for children aged five to six years was extremely strong. Yet their confidence intervals overlapped with other age groups, indicating no significant differences in efficacy across K-12 students. This aligns with Kazu and Yalçın (2021), whose meta-analysis found no statistically significant variation in STEM learning outcomes by educational level (age group), emphasising STEM's consistent academic benefits regardless of student stage. Future research should focus on tailoring age-specific instructional strategies to further enhance learning outcomes within this universal effectiveness. The results showed that disability type had a moderating effect. Owing to the many overlapping clinical features between ID and ASD, especially regarding social communication, imagination and repetitive, stereotyped behaviours, individuals with comorbid ID and ASD often had more severe impairments than those with ID alone (Cen et al., 2017). Other studies have indicated that population with comorbid ID and ASD exhibit a higher incidence of maladaptive behaviours, psychopathology and emotional difficulties than those without ASD (Brereton et al., 2006). Overall, students with co-occurring ASD and ID have lower abilities in STEM-related areas than those with other single disability types (Martin et al., 2020) and might have more cognitive difficulties, which could make it challenging for them to apply the skills or behaviours learned in specific environments to other settings. This might affect the maintenance and generalisation of intervention effects (Sigafoos et al. 2008). When teachers carry out STEM teaching, they should consider the practical needs of different types of disabilities. Since sex and age have no moderating effect, we believe that STEM education is suitable for all age groups and genders. Research has shown that exposing young children to STEM is crucial for fostering their learning interest and enhancing their academic and employment achievements (Noonan, 2017). Moreover, Brigham et al. (2011) believed that the earlier students were exposed to STEM education, the better they understood STEM content. Frontline teaching practices can pay more attention to this group.

Intervention processes. The results revealed no moderating effects of intervention settings, interventionists, or intervention duration. Research indicates that the interdisciplinary nature of STEM enables it to function in various intervention settings (Borda et al., 2020). Considering the increasing number of students receiving inclusive education and their desire to participate in society (Fleury et al., 2014), more research can focus on conducting studies in inclusive classrooms and communities to enhance students' social adaptability. About half of the studies included interventions implemented by professional researchers and the effects were extremely strong. Professionals could use specialised assessment tools and resources to design and implement effective intervention plans based on students' situations and objectively assess their condition and progress (Kasari et al., 2012). Israel et al. (2013) suggested that selecting interventionists in STEM education depended on the grade levels of students with ID and ASD, STEM areas, teaching settings and teachers' familiarity with the STEM content. Future efforts should be committed to promoting interdisciplinary teacher collaboration, integrating general education teachers, special education teachers and researchers to form interdisciplinary teaching teams. These teams will jointly conduct joint lesson preparation, teaching behaviour analysis and carry out research on practical problems in teaching to enhance STEM education quality (Wu, 2022). This study's results revealed that the best interventions were performed less than ten times, with an effect size of one; in addition, other durations showed strong-to-extremely strong effects. The reason may be attributed to the unique characteristics of students with ASD and students with ID, resulting in a higher prevalence of SCD currently being conducted(Iatraki and Soulis, 2021), with significant variations in experimental designs among these studies and intervention procedures for different skills across various STEM domains not being uniform. However, the number of interventions with a duration of less than ten sessions was limited; therefore, further validation is required to ensure the robustness of this result. Future studies can also longitudinally analyse the impact of intervention frequency on outcomes and explore the relationships between moderating variables. Research indicates that teaching STEM to those individuals were not restricted by the settings, interventionists, or intervention duration. This finding not only demonstrates their potential to participate in and benefit from STEM learning but also reflects the flexibility and adaptability of the STEM approach. More importantly, this finding emphasises the necessity of providing equal STEM learning opportunities for students with ASD and students with ID.

Limitations and future directions. This study had several limitations. First, studies on teaching STEM education to ID and ASD students have focused on the mathematics, science and technology domains; as such, there was a lack of research in engineering and interdisciplinary STEM areas. Therefore, future STEM education should continue to enrich research in these areas. Additionally, future longitudinal studies on students with ASD and students with ID are also needed. Educators can observe the generalisation effects over time to better understand the developmental process of STEM skills in this population and assess the long-term trends in STEM education.

Second, although WOS provides extensive literature resources, its coverage is biased and excludes other databases and grey literature, potentially affecting the study's comprehensiveness. Our systematic review and meta-analysis may not fully represent the research. Future research should integrate other databases such as Scopus, ERIC, PubMed, Springer and Elsevier databases and grey literature to provide a more comprehensive review and reduce potential publication bias.

Third, this study excluded randomised controlled experiments and qualitative studies and concentrated solely on single-case studies. This limitation restricted the interpretation of the findings and introduced a potential risk of bias. Although a meta-analysis was valuable for summarising the effects of STEM interventions in individuals with ID and ASD, future reviews could use other methods (e.g. systematic reviews, RCTs, mixed-methods approaches).

Fourth, this study did not examine the impact of disability severity on STEM intervention effectiveness and included few participants with severe ID. This results in insufficient attention to students with high support needs, who are key targets for assistive technologies (e.g. brain-computer interfaces, neurofeedback). Future research should thoroughly investigate the impact of disability severity (e.g. from mild to severe) on STEM teaching effectiveness, focus on developing adaptive STEM teaching programmes based on cognitive ability stratification and evaluate the effectiveness of various assistive technologies.

Implications for research and practice. The research indicates that STEM interventions are effective for students with ASD and students with ID, demonstrating that STEM can provide rich learning experiences, ameliorate academic difficulties and facilitate better engagement in learning activities for this population, enhancing their understanding of the world. In addition to academic abilities, it promotes students' enquiry skills, problem-solving capabilities and social competencies (Hutchison et al., 2024; De Loof et al., 2022). While the study highlights maintenance and generalisation effectiveness, research remains concentrated in mathematics, science and technology, with gaps in engineering and limited interdisciplinary studies, and a lack of long-term outcome validation. Accordingly, we propose dual recommendations: policymakers should prioritise the development of engineering-focused educational programmes and establish a 'STEM + Humanities and Arts' integrated framework, such as expanding interdisciplinary approaches in the arts (i.e. dance, music, theatre, visual arts and media arts) (Hwang and Taylor, 2016; Perignat and Katz-Buonincontro, 2019) and social sciences to enhance students' holistic competencies. Additionally, implement legislation to improve in transparency special education budget allocation. Researchers should use longitudinal designs to investigate the long-term effects of STEM learning, focusing on core indicators such as skill retention, transfer efficacy in community settings, vocational training completion rates and higher education enrolment/attrition rates. Furthermore, explore the mechanisms through which school support systems influence STEM achievement for students with disabilities.

This study summarises optimal STEM interventions across domains and highlights diversified teaching strategies for students with varying disabilities. To effectively implement STEM interventions, we propose a 'Teacher Development System for Inclusive STEM Practice'. First, differentiated instructional design involves creating adaptive teaching frameworks with tiered interventions tailored to students' diverse needs. By integrating interdisciplinary approaches (e.g. integrating art into mathematics, combining science with engineering, or using robotics for social skill training), reducing learning gaps for ASD/ID students while enhancing teachers' interdisciplinary teaching skills. Second, training in emerging assistive technologies equips educators to utilise adaptive learning platforms, VM, AI feedback and AR/VR simulations to support students' executive function development (Ayeni et al., 2024). Real-time analytics should be used to monitor participation in STEM activities, enabling dynamic assessments and adjustments to support levels, task difficulty and technical assistance intensity (Nuangchalerm and Prachagool, 2023). Third, establish cross-departmental partnerships between special education and STEM teachers to co-design STEM + X thematic modules (e.g. 'Eco-Engineering Community Solutions') using universal design principles. Develop localised resource libraries, including adaptive technology toolkits and differentiated assessment plans, to help teachers optimise instruction by accessing intervention components in real-time.

This study also explored the variables that affect the effectiveness of STEM learning and the results indicated that different types of disabilities significantly impact learning outcomes. In particular, most studies have overlooked the academic performance of students with ASD-ID (Russell et al., 2019). This study fills that gap. Future studies should delve deeper into how cultural and socioeconomic backgrounds shape STEM learning experiences for students with ID and ASD. For instance, cross-cultural comparisons could uncover how cultural scripts influence STEM motivation and engagement for these students, revealing how educational philosophies and methods in diverse cultural contexts affect learning outcomes. Additionally, research should investigate socioeconomic factors such as family income, accessibility of educational resources and the strength of community support systems, as these elements can influence STEM learning opportunities and effectiveness. By considering these variables comprehensively, we can provide more targeted and effective educational support for students with ASD and students with ID, helping them integrate into society and enhance their quality of life.

Overall, this systematic review and meta-analysis offer comprehensive insights into the effectiveness of STEM teaching for students with ASD and students with ID, the prospects of enhancing STEM skills and the influence of moderating variables on STEM learning outcomes. These findings could inform instructors, educational practitioners and policymakers in identifying potential challenges and promoting the development of STEM education.

Data availability

All data generated or analysed during this study are included within the article and its supplementary information files.

Received: 20 August 2024; Accepted: 10 June 2025;
Published online: 04 July 2025

Note

1 ID and ASD mentioned in this study can be found in The Diagnostic and Statistical Manual of Mental Disorders (Fifth Edition) (DSM-5)

References

Amaral D, Geschwind D, Dawson G (2011) Autism spectrum disorders. Oxford University Press, USA

Al-Ahmadi F, Oraif F (2009) Working memory capacity, confidence, and scientific thinking. Res Sci Technol Educ 27(2):225–243. https://doi.org/10.1080/02635140902853673

Allison DB, Gorman BS (1993) Calculating effect sizes for meta-analysis: the case of the single case∗. Behav Res Ther 31(6):621–631. https://doi.org/10.1016/0005-7967(93)90115-B

Alresheed F, Machalicek W, Sanford A, Bano C (2018) Academic and related skills interventions for autism: a 20-year systematic review of single-case research. Rev J Autism Dev Disord 5(4):311–326. https://doi.org/10.1007/s40489-018-0141-9

Archer AL, Hughes CA (2011) Explicit instruction: effective and efficient teaching. The Guilford Press, New York

Ayeni OO, Unachukwu CC, Osawaru B, Chisom ON, Adewusi OE (2024) Innovations in STEM education for students with disabilities: a critical examination. Int J Sci Res Arch 11(1):1797–1809. https://doi.org/10.30574/ijsra.2024.11.1.0285

Ayeni AO, Ovbiye RE, Onayemi AS, Ojedele KE (2024) AI-powered adaptive learning platforms: enhancing educational outcomes for students with special needs. World J Adv Res Rev 22(3):2253–2265. https://doi.org/10.30574/wjarr.2024.22.3.0843

Aykut Ç, Dayi E, Emecen DD, Karasu N (2012) Teaching chained tasks to students with intellectual disabilities using video prompting in small group instruction. Educ Sci Theory Pract 14(3):1082–1087

Banda DR, Dogoe MS (2011) Review of video prompting studies with persons with developmental disabilities. Educ Train Autism Dev Disabil 46(4):514–527

Basham JD, Israel M, Maynard K (2010) An ecological model of STEM education: operationalizing STEM for all. J Spec Educ Technol 25(3):9–19. https://doi.org/10.1177/016264341002500303

Benallie KJ, McClain MB, Bakner KE, Roanhorse T, Ha J (2021) Executive functioning in children with ASD + ADHD and ASD + ID: a systematic review. Res Autism Spect Dis 86:101807

Bers MU, Flannery L, Kazakoff ER, Sullivan A (2014) Computational thinking and tinkering:exploration of an early childhood robotics curriculum. Comput Educ 72:145–157. https://doi.org/10.1016/j.compedu.2013.10.020

Bitsko RH, Claussen AH, Lichstein J, Black LI, Jones SE, Danielson ML, Hoenig JM, Davis Jack SP, Brody DJ, Gyawali S, Maenner MJ, Warner M, Holland KM, Perou R, Crosby AE, Blumberg SJ, Avenevoli S, Kaminski JW, Ghandour RM, Meyer LN (2022) Mental health surveillance among children—United States, 2013–2019. MMWR Suppl 71(2):1–42. https://doi.org/10.15585/mmwr.su7102a1

Borda E, Haskell T, Boudreaux A (2020) Cross-disciplinary learning: a framework for assessing application of concepts across STEM disciplines (Version 1). arXiv. https://doi.org/10.48550/ARXIV.2012.07906

Breiner JM, Harkness SS, Johnson CC, Koehler CM (2012) What is STEM? a discussion about conceptions of STEM in education and partnerships. Sch Sci Math 112(1):3–11. https://doi.org/10.1111/j.1949-8594.2011.00109.x

Brereton AV, Tonge BJ, Einfeld SL (2006) Psychopathology in children and adolescents with autism compared to young people with intellectual disability. J Autism Dev Disord 36(7):863–870. https://doi.org/10.1007/s10803-006-0125-y

Brigham FJ, Scruggs TE, Mastropieri MA (2011) Science education and students with learning disabilities. Learn Disabil Res Pract 26(4):223–232. https://doi.org/10.1111/j.1540-5826.2011.00343.x

Cen CQ, Liang YY, Chen QR, Chen KY, Deng HZ, Chen BY, Zou XB (2017) Investigating the validation of the chinese mandarin version of the social responsiveness scale in a mainland China child population. BMC Psychiatr 17(1):51. https://doi.org/10.1186/s12888-016-1185-y

Corbett BA, Constantine LJ, Hendren R, Rocke D, Ozonoff S (2009) Examining executive functioning in children with autism spectrum disorder, attention deficit hyperactivity disorder and typical development. Psychiatry Res 166(2–3):210–222. https://doi.org/10.1016/j.psychres.2008.02.005

De Loof H, Boeve-de Pauw J, Van Petegem P (2022) Integrated STEM education: the effects of a long-term intervention on students' cognitive performance. Eur J STEM Educ 7(1):13. https://doi.org/10.20897/ejsteme/12738

Delano ME (2007) Video modeling interventions for individuals with autism. Remedial Spec Educ 28(1):33–42. https://doi.org/10.1177/07419325070280010401

Di Blasi FD, Costanzo AA, Finocchiaro M, Stimoli MA, Zuccarello R, Buono S, Ferri R, Zoccolotti P (2023) Academic skills in students with autism spectrum disorder and intellectual disability: a systematic review and meta-analysis. Educ Sci 13(10):1026. https://doi.org/10.3390/educsci13101026

Diehl JJ, Schmitt LM, Villano M, Crowell CR (2012) The clinical use of robots for individuals with autism spectrum disorders: a critical review. Res Autism Spectr Disord 6(1):249–262. https://doi.org/10.1016/j.rasd.2011.05.006

Doabler CT, Fien H (2013) Explicit mathematics instruction: what teachers can do for teaching students with mathematics difficulties. Inter Sch Clin 48(5):276–285. https://doi.org/10.1177/1053451212473151

Dykens EM, Lense M (2011) Intellectual disabilities and autism spectrum disorder: a cautionary note. In: Amaral D, Geschwind D, Dawson G (eds) Autism spectrum disorders, pp 263–269. Oxford University Press

Ehsan H, Rispoli M, Lory C, Gregori E (2018) A systematic review of STEM instruction with students with autism spectrum disorders. Rev J Autism Dev Disord 5(4):327–348. https://doi.org/10.1007/s40489-018-0142-8

Elliott R (2003) Executive functions and their disorders. Br Med Bull 65(1):49–59. https://doi.org/10.1093/bmb/65.1.49

Fleury VP, Hedges S, Hume K, Browder DM, Thompson JL, Fallin K, El Zein F, Reutebuch CK, Vaughn S (2014) Addressing the academic needs of adolescents with autism spectrum disorder in secondary education. Remedial Spec Educ 35(2):68–79. https://doi.org/10.1177/0741932513518823

Gunning C, Holloway J, Fee B, Breathnach Ó, Bergin CM, Greene I, Ní Bheoláin R (2019) A systematic review of generalisation and maintenance outcomes of social skills intervention for preschool children with autism spectrum disorder. Rev J Autism Dev Disord 6(2):172–199. https://doi.org/10.1007/s40489-019-00162-1

Guo S, Zheng Y, Zhai X (2024) Artificial intelligence in education research during 2013–2023: a review based on bibliometric analysis. Educ Inf Technol 29(13):16387–16409. https://doi.org/10.1007/s10639-024-12491-8

Hart JE, Whalon KJ (2008) Promote academic engagement and communication of students with autism spectrum disorder in inclusive settings. Int Sch Clin 44(2):116–120. https://doi.org/10.1177/1053451207310346

Heinrich S, Collins BC, Knight V, Spriggs AD (2016) Embedded simultaneousprompting procedure to teach STEM content to high school students withmoderate disabilities in an inclusive setting. Educ Train Autism Dev Disabil 51(1):41–54

Hill EL (2004) Executive dysfunction in autism. Trends Cogn Sci 8(1):26–32. https://doi.org/10.1016/j.tics.2003.11.003

Hong ER, Ganz JB, Mason R, Morin K, Davis JL, Ninci J, Neely LC, Boles MB, Gilliland WD (2016) The effects of video modelling in teaching functional living skills to persons with ASD: a meta-analysis of single-case studies. Res Dev Disabil 57:158–169. https://doi.org/10.1016/j.ridd.2016.07.001

Horner RH, Carr EG, Halle J, McGee G, Odom S, Wolery M (2005) The use of single-subject research to identify evidence-based practice in special education. Except Child 71(2):165–179. https://doi.org/10.1177/001440290507100203

Huang SQ, Zhu H, He HZ (2023) Can ICT-based interventions improve the reading ability of students with autism spectrum disorder? A meta-analysis based on 40 single-subject studies. e-Educ Res 44(3):99–106+114. https://doi.org/10.13811/j.cnki.eer.2023.03.014

Hughes CE, Dieker LA, Glavey EM, Hines RA, Wilkins I, Ingraham K, Bukaty CA, Ali K, Shah S, Murphy J, Taylor MS (2022) RAISE: robotics and AI to improve STEM and social skills for elementary school students. Front Virtual Real 3:968312

Hutchison A, Barnard-Brak L, Renda C (2024) Advancing STEM learning opportunities for students with autism spectrum disorder through an informal robotics and coding program: a feasibility study for an after-school enrichment program. J Technol Behav Sci. https://doi.org/10.1007/s41347-024-00453-3

Hwang J, Taylor J (2016) Stemming on STEM: a STEM education framework for students with disabilities. J Sci Educ Stud Disabil 19(1):39–49. https://doi.org/10.14448/jsesd.06.00017

Iatraki G, Soulis SG (2021) A systematic review of single-case research on science-teaching interventions to students with intellectual disability or autism spectrum disorder. Disability 1(3):286–300. https://doi.org/10.3390/disabilities1030021

Israel M, Maynard K, Williamson P (2013) Promoting literacy-embedded, authentic STEM instruction for students with disabilities and other struggling learners. Teach Child 45(4):18–25. https://doi.org/10.1177/004005991304500402

Jimenez BA, Browder DM, Courtade GR (2009) An exploratory study of self-directed science concept learning by students with moderate intellectual disabilities. Res Pr Pers Sev Disabil 34(2):33–46. https://doi.org/10.2511/rpsd.34.2.33

Jitendra AK, Nelson G, Pulles SM, Kiss AJ, Houseworth J (2016) Is mathematical representation of problems an evidence-based strategy for students with mathematics difficulties? Child 83(1):8–25. https://doi.org/10.1177/0014402915625062

Karp T, Maloney P (2013) Exciting young students in grades K-8 about STEM through an afterschool robotics challenge. Am J Eng Educ 4(1):39–54. https://doi.org/10.19030/ajee.v4i1.7857

Kasari C, Gulsrud A, Freeman S, Paparella T, Hellemann G (2012) Longitudinal follow-up of children with autism receiving targeted interventions on joint attention and play. J Am Acad Child Adolesc Psychiatr 51(5):487–495. https://doi.org/10.1016/j.jaac.2012.02.019

Kazu IY, Yalçın CK (2021) The effect of STEM education on academic performance: a meta-analysis study. Turk Online J Educ Technol 20(4):101–116

Kennedy CH, Shukla S, Fryxell D (1997) Comparing the effects of educational placement on the social relationships of intermediate school students with severe disabilities. Child 64(1):31–47. https://doi.org/10.1177/001440299706400103

Knight V, McKissick BR, Saunders A (2013a) A review of technology-based interventions to teach academic skills to students with autism spectrum disorder. J Autism Dev Disord 43(11):2628–2648. https://doi.org/10.1007/s10803-013-1814-y

Knight VF, Smith BR, Spooner F, Browder D (2012) Using explicit instruction to teach science descriptors to students with autism spectrum disorder. J Autism Dev Disord 42(3):378–389. https://doi.org/10.1007/s10803-011-1258-1

*Knight VF, Spooner F, Browder DM, Smith BR, Wood CL (2013b) Using systematic instruction and graphic organisers to teach science concepts to students with autism spectrum disorders and intellectual disability. Focus Autism Other Dev Disabil 28(2):115–126. https://doi.org/10.1177/1088357612475301

Knight VF, Kuntz EM, Brown M (2018) Paraprofessional-delivered video prompting to teach academics to students with severe disabilities in inclusive settings. J Autism Dev Disord 48(6):2203–2216. https://doi.org/10.1007/s10803-018-3476-2

Knol MJ, Pestman WR, Grobbee DE (2011) The (mis)use of overlap of confidence intervals to assess effect modification. Eur J Epidemiol 26(4):253–254. https://doi.org/10.1007/s10654-011-9563-8

Kotsi S, Handrinou S, Iatraki G, Soulis SG (2025) A review of artificial intelligence interventions for students with autism spectrum disorder. Disabilities 5(1):7. https://doi.org/10.3390/disabilities5010007

Kruskal WH, Wallis WA (1952) Use of ranks in one-criterion variance analysis. J Am Stat Assoc 47(260):583–621. https://doi.org/10.1080/01621459.1952.10483441

Leung RC, Zakzanis KK (2014) Brief report: cognitive flexibility in Autism spectrum disorders: a quantitative review. J Autism Dev Disord 44(10):2628–2645. https://doi.org/10.1007/s10803-014-2136-4

Lin LY, Hwang IT, Hsu CF, Yu WH, Lai PC, Chen YW, Tu YF (2024) Comparing fine motor performance among young children with autism spectrum disorder, intellectual disability, attention-deficit/hyperactivity disorder, and specific developmental disorder of motor function. Front Pediatr 12:1372980. https://doi.org/10.3389/fped.2024.1372980

Lindsay S, Kolne K, Oh A, Cagliostro E (2019) Children with disabilities engaging in STEM: Exploring how a group-based robotics program influences STEM activation. Can J Sci Math Technol Educ 19(4):387–397. https://doi.org/10.1007/s42330-019-00061-x

*Liu D, Lory C, Lei Q, Cai W, Mao Y, Yang X (2023) Using explicit instruction and virtual manipulatives to teach measurement concepts for students with autism spectrum disorder. J Special Educ 002246692311715. https://doi.org/10.1177/00224669231171558

Martin WB, Yu J, Wei X, Vidiksis R, Patten KK, Riccio A (2020) Promoting science, technology, and engineering self-efficacy and knowledge for all with an autism inclusion maker program. Front Educ 5:75. https://doi.org/10.3389/feduc.2020.00075

Matson JL, Dempsey T, LoVullo SV (2009) Characteristics of social skills for adults with intellectual disability, autism and PDD-NOS. Res Autism Spec Disord 3(1):207–213. https://doi.org/10.1016/j.rasd.2008.05.006

Miller B (2012) Ensuring meaningful access to the science curriculum for students with significant cognitive disabilities. Teach Child 44(6):16–25. https://doi.org/10.1177/004005991204400602

*Miller B (2015) Using science inquiry methods to promote self-determination and problem-solving skills for students with moderate intellectual disability. Dissertation, Purdue University https://www.proquest.com/openview/e4bd1461547c40a8358b5146f4d5e768/1?pq-origsite=gscholar&cbl=18750

Murthi K, Chen YL, Martin W, Riccio A, Patten K (2024) Understanding STEM outcomes for autistic middle schoolers in an interest-based, afterschool program: a qualitative study. Res Sci Educ 54(4):595–620. https://doi.org/10.1007/s11165-024-10158-5

Nachman BR, Kim H, Liu C, Ottens M, Cook K, Cates G (2024) The current state of knowledge regarding STEM career pathways for students with autism: a systematic literature review. J Postsecond Educ Disabil 37(2):115–130

National Academy of Engineering and National Research Council (2002) Technically speaking: why all Americans need to know more about technology. National Academies Press, Washington, DC

National Research Council (1996) National Science Education Standards. National Academies Press, Washington, DC

National Research Council, Committee on Development of an Addendum to the National Science Education Standards on Scientific Inquiry, Center for Science, Mathematics, and Engineering Education (2000) Inquiry and the national science education standards: a guide for teaching and learning. National Academies Press, Washington, DC

National Science Foundation, Division of Science Resources Statistics (2004) Science and engineering degrees: 1966–2001. NSF 04-311, Project Officers ST Hill, JM Johnson. https://wayback.archive-it.org/5902/20150629122556/http://www.nsf.gov/statistics/nsf04311/pdf/front.pdf

Ninci J, Neely LC, Burke MD, Rispoli M, Vannest KJ, Willson V, Ulloa P (2020) A meta-analysis of single-case research on embedding interests of individuals with autism spectrum disorder. Remedial Spec Educ 41(5):296–308. https://doi.org/10.1177/0741932519841692

Noonan R (2017) STEM jobs: 2017 update. US Department of Commerce Economics and Statistics Administration. https://www.commerce.gov/sites/default/files/migrated/reports/stem-jobs-2017-update.pdf

Nuangchalerm P, Prachagool V (2023) AI-driven learning analytics in STEM education. Int J Res STEM Educ 5(2):77–84. https://doi.org/10.33830/ijrse.ijrse.v5i2.1596

Oswald TM, Beck JS, Iosif A, McCauley JB, Gilhooly LJ, Matter JC, Solomon M (2016) Clinical and cognitive characteristics associated with mathematics problem-solving in adolescents with autism spectrum disorder. Autism Res 9(4):480–490. https://doi.org/10.1002/aur.1524

Ozkan F, Kettler T (2022) Effects of STEM education on the academic success and social-emotional development of gifted students. J Gift Educ Creat

Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Moher D (2021) Preferred reporting items for systematic reviews and meta-analyses 2020 statement: an updated guideline for reporting systematic reviews. Br Med J 372(71). https://doi.org/10.1136/bmj.n71

Park J, Bouck E, Duenas A (2019) The effect of video modeling and video prompting interventions on individuals with intellectual disability: a systematic literature review. J Spec Educ Technol 34(1):3–16. https://doi.org/10.1177/0162643418780464

Parker RI, Vannest KT (2009) An improved effect size for single-case research: nonoverlap of all pairs. Behav Ther 40(4):357–367. https://doi.org/10.1016/j.beth.2008.10.006

Pan CY, Kuo TY, Kuo FL (2023) Meta-analysis of effectiveness of parent-mediated telehealth interventions in children with autism spectrum disorder. Res Autism Spectr Disord 107:102209. https://doi.org/10.1016/j.rasd.2023.102209

Parker RI, Vannest KJ, Davis JL, Sauber SB (2011) Combining nonoverlap and trend for single-case research: Tau-U. Behav Ther 42(2):284–299. https://doi.org/10.1016/j.beth.2010.08.006

Payton ME, Greenstone MH, Schenker N (2003) Overlapping confidence intervals or standard error intervals: what do they mean in terms of statistical significance? J Insect Sci 3(34):1–6. https://doi.org/10.1673/031.003.3401

Pérez VE, Lorenzo G, Lorenzo LA, Lledó A (2024) Analysis of the application of the Bee-Bot robot for the development of social reciprocity skills in students with autism spectrum disorder. Int J Soc Robot. https://doi.org/10.1007/s12369-024-01099-0

Perignat E, Katz-Buonincontro J (2019) STEAM in practice and research: an integrative literature review. Think Skills Creat 31:31–43

Reichow B, Volkmar FR, Cicchetti DV (2008) Development of the evaluative method for evaluating and determining evidence-based practices in autism. J Autism Dev Disord 38(7):1311–1319. https://doi.org/10.1007/s10803-007-0517-7

Reichow B, Barton EE, Maggin DM (2018) Development and applications of the single-case design risk of bias tool for evaluating single-case design research study reports. Res Dev Disabil 79:53–64. https://doi.org/10.1016/j.ridd.2018.05.008

Rittle-Johnson B (2017) Developing mathematics knowledge. Child Dev Perspect 11(3):184–190. https://doi.org/10.1111/cdep.12229

*Rockwell SB, Griffin CC, Jones HA (2011) Schema-based strategy instruction in mathematics and the word problem-solving performance of a student with autism. Focus Autism Other Dev Disabil 26(2):87–95. https://doi.org/10.1177/1088357611405039

Roelofs RL, Visser EM, Berger HJC, Prins JB, Van Schrojenstein Lantman-De Valk HMJ, Teunisse JP (2015) Executive functioning in individuals with intellectual disabilities and autism spectrum disorders. J Intellect Disabil Res 59(2):125–137. https://doi.org/10.1111/jir.12085
Russell G, Mandy W, Elliott D, White R, Pittwood T, Ford T (2019) Selection bias on intellectual ability in autism research: a cross-sectional review and meta-analysis. Mol Autism 10(1):9. https://doi.org/10.1186/s13229-019-0260-x
Suzuki Y, Wild F, Scanlon E (2024) Measuring cognitive load in augmented reality with physiological methods: a systematic review. J Comput Assist Learn 40(2):375–393. https://doi.org/10.1111/jcal.12882
Sansosti FJ, Doolan ML, Remaklus B, Krupko A, Sansosti JM (2015) Computer-assisted interventions for students with autism spectrum disorders within school-based contexts: a quantitative meta-analysis of single-subject research. Rev J Autism Dev Disord 2(2):128–140. https://doi.org/10.1007/s40489-014-0042-5
Schenker N, Gentleman JF (2001) On judging the significance of differences by examining the overlap between confidence intervals. Am Stat 55(3):182–186. https://doi.org/10.1198/000313001317097960
Schreffler J, Vasquez III E, Chini J, James W (2019) Universal design for learning in postsecondary STEM education for students with disabilities: a systematic literature review. Int J STEM Educ 6(1):8. https://doi.org/10.1186/s40594-019-0161-8
Schaefer Whitby PJ (2013) The effects of Solve It! on the mathematical wordproblem-solving ability of adolescents with autism spectrum disorders FocusAutism Other Dev Disabil 28(2):78–88. https://doi.org/10.1177/1088357612468764
Selanikyo E, Yalon-Chamovitz S, Weintraub N (2017) Enhancing classroom participation of students with intellectual and developmental disabilities. Can J Occup Ther 84(2):76–86. https://doi.org/10.1177/0008417416661346
Shams L, Seitz AR (2008) Benefits of multisensory learning. Trends Cogn Sci 12(11):411–417. https://doi.org/10.1016/j.tics.2008.07.006
Sigafoos J, Ganz J, O'Reilly M, Lancioni G (2008) Evidence-based practice in the classroom: evaluating a procedure for reducing perseverative requesting in an adolescent with autism and severe intellectual disability. Australas J Spec Educ 32(1):55–65. https://doi.org/10.1017/S1030011200025756
Simpkins PM, Mastropieri MA, Scruggs TE (2009) Differentiated curriculum enhancements in inclusive fifth-grade science classes. Remed Spec Educ 30(5):300–308. https://doi.org/10.1177/0741932508321011
Smith ML, Glass GV (1977) Meta-analysis of psychotherapy outcome studies. Am Psychol 32(9):752–760. https://doi.org/10.1037/0003-066X.32.9.752
Spooner F, Knight V, Browder D, Jimenez B, DiBiase W (2011) Evaluating evidence-based practice in teaching science content to students with severe developmental disabilities. Res Pract Pers Sev Disabil 36(1–2):62–75. https://doi.org/10.2511/rpsd.36.1-2.62
Srivastava AK, Schwartz CE (2014) Intellectual disability and autism spectrum disorders: causal genes and molecular mechanisms. Neurosci Biobehav Rev 46:161–174. https://doi.org/10.1016/j.neubiorev.2014.02.015
Stierle J, Ryan J, Katsiyannis A, Mims P (2023) Using video prompting and modeling on mobile technology to teach daily living skills: a systematic review. Adv Neurodev Disord 7(4):491–501. https://doi.org/10.1007/s41252-022-00273-7
Strnadová I, Cumming TM, Danker J (2016) Transitions for students with intellectual disability and/or autism spectrum disorder: carer and teacher perspectives. Aust J Spec Educ 40(2):141–156. https://doi.org/10.1017/jse.2016.2
Tang RL, Peng TT, Zhu N (2023) The effect of social story interventions on people with autism spectrum disorder: a meta-analysis of single-subject experimental studies. Chin J Spec Educ 2:61–71
Thomas EM, DeBar RM, Vladescu JC, Townsend DB (2020) A comparison of video modeling and video prompting by adolescents with ASD. Behav Anal Pract 13(1):40–52. https://doi.org/10.1007/s40617-019-00402-0
Veinott ES (2022) Adaptive instruction: a case study of gamified practice and testing in a large introductory psychology course. In: G Meiselwitz A Moallem P, Zaphiris A, Ioannou RA, Sottilare J, Schwarz, X Fang (Eds), HCI international 2022—late breaking papers. interaction in new media, learning and games Vol 13517, Springer Nature Switzerland, pp 455–467 https://doi.org/10.1007/978-3-031-22131-6_34
Verté S, Geurts HM, Roeyers H, Oosterlaan J, Sergeant JA (2006) Executive functioning in children with an autism spectrum disorder: can we differentiate within the spectrum? J Autism Dev Disord 36(3):351–372. https://doi.org/10.1007/s10803-006-0074-5
Vivanti G, Barbaro J, Hudry K, Dissanayake C, Prior M (2013) Intellectual development in autism spectrum disorders: new insights from longitudinal studies. Front Hum Neurosci 7. https://doi.org/10.3389/fnhum.2013.00354
Wehmeyer ML, Palmer SB, Agran M, Mithaug DE, Martin JE (2000) Promoting causal agency: the self-determined learning model of instruction. Child 66(4):439–453. https://doi.org/10.1177/001440290006600401
Williams JP, Stafford KB, Lauer KD, Hall KM, Pollini S (2009) Embedding reading comprehension training in content-area instruction. J Educ Psychol 101(1):1–20. https://doi.org/10.1037/a0013152
Wolery M, Dunlap G (2001) Author and reviewer guideline series: reporting on studies using single-subject experimental methods. J Early Inter 24(2):85–89. https://doi.org/10.1177/105381510102400201
Wright JC, Knight VF, Barton EE (2020) A review of video modelling to teach STEM to students with autism and intellectual disability. Res Autism Spectr Disord 70:101476. https://doi.org/10.1016/j.rasd.2019.101476
Wu Z (2022) Understanding teachers' cross-disciplinary collaboration for STEAM education: building a digital community of practice. Think Skills Creat 46:101178. https://doi.org/10.1016/j.tsc.2022.101178
Yuen TT, Mason LL, Gomez A (2014) Collaborative robotics projects for adolescents with autism spectrum disorders. J Spec Educ Technol 29(1):51–62. https://doi.org/10.1177/016264341402900104
Zhou S, Dong Z, Wang HH, Chiu MM (2024) A meta-analysis of STEM integration on student academic achievement. Res Sci Educ https://doi.org/10.1007/s11165-024-10216-y
Zollman A (2012) Learning for STEM literacy: STEM literacy for learning. Sch Sci Math 112(1):12–19. https://doi.org/10.1111/j.1949-8594.2012.00101.x

Acknowledgements
This research was supported by the National Social Science Fund of China (21&ZD293), National Social Science Fund of China (BGA220153) and National Social Science Fund of Shaanxi Province (2022P025).

Author contributions
Fang Da: Conceptualisation of the research, manuscript writing, data collection and analysis and revision and supervision of the research. Ying Ma and Minjie Ma: Manuscript writing, data collection and analysis. Jieyu Mao, Zijiang Weng and Chao Yang: Manuscript revision. Tingzhao Wang: funding acquisition, revision and supervision of the research and final approval of the version to be published.

Ethical approval
Ethical approval was not required as the study did not involve human participants.

Informed consent
Informed consent was not required as the study did not involve human participants.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-025-05292-y.

Correspondence and requests for materials should be addressed to Tingzhao Wang.