

From Virtual Modeling to 3D Making: A Multi-Study Evaluation of Inclusive Digital Fabrication for Students with Disabilities

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ABSTRACT:

Students with disabilities often have limited access to advanced digital fabrication despite its potential to support visual, spatial, technical, and participatory learning. This multi-study mixed-methods evaluation examined an inclusive pathway integrating interactive desktop 3D modeling, 3D printing, product development, and digital promotion. Study 1 involved 30 students with autism spectrum disorder aged 767-780 years in a single-group pretest-posttest evaluation of desktop 3D modeling. Study 2 drew on a 12-month community digital-fabrication program involving approximately 60 students with special educational needs, with complete paired applied-skills data available for 19 participants. In Study 1, spatial ability increased from $M = 44.83$ to 49.50 , $t(29) = -3.43$, $p = .002$, $d_z = 0.63$, and learning confidence increased from $M = 45.37$ to 48.47 , $t(29) = -2.73$, $p = .011$, $d_z = 0.50$. In Study 2, understanding of 3D printing, 3D-design skills, and printing-process understanding improved significantly, with large within-sample effects ($d_z = 0.767-780.32$). Qualitative and program evidence highlighted visual engagement, active exploration, autonomy, peer support, and progression from virtual models to physical products and public-facing presentation. The findings suggest that carefully scaffolded digital-to-physical making can support technical competence, confidence, agency, and participation, although the absence of comparison groups and incomplete archival measurement documentation limit causal conclusions.

Keywords: special education technology, interactive 3D modeling, digital fabrication, 3D printing, autism spectrum disorder

1. Introduction

Educational technology in special education is increasingly moving beyond compensatory

access tools toward technologies that enable students with disabilities to participate in complex academic, creative, and vocationally relevant activities. A recent ten-year review of

research in the Journal of Special Education Technology (JSET) documented the widening range of emerging technologies used to support academic, behavioral, adaptive, and participation outcomes for individuals with disabilities (Carreon et al., 2026). This development creates an important design challenge. Access to a device or application is not sufficient if students are not given structured opportunities to manipulate information, solve problems, create artifacts, and demonstrate competence in ways that connect technology use with meaningful learning.

Virtual reality (VR) is one example. Research with students with disabilities has grown as screen-based, semi-immersive, and immersive systems have become more accessible. Carreon et al. (2022) found that much K-12 VR research with students with disabilities relied on nonimmersive or screen-based simulations, suggesting that educational value does not depend exclusively on head-mounted displays. JSET research has also shown that desktop VR can support sustained social and design activity for children with autism spectrum disorder (ASD; Ke et al., 2022), while recent work emphasizes that successful VR environments should be informed by the preferences and experiences of students and teachers rather than by technological novelty alone (Carreon et al., 2025). Current reviews continue to identify promising outcomes for VR with children with ASD, but they also note heterogeneity in designs, measures, and educational targets (Fu et al., 2025).

One educational use that remains less developed in the special education technology literature is digital fabrication. Digital fabrication combines computer-aided design, three-dimensional (3D) modeling, and physical production. This is potentially valuable for students with disabilities because it externalizes abstract ideas into visible and tangible artifacts. In special education environments, 3D printing has been used to create accessible learning materials and to involve students directly in design and production (Buehler et al., 2014). More broadly, maker education has been associated with creativity, design thinking, collaboration, and

technology-related self-efficacy when activities are structured around iterative creation rather than passive tool use (Davies & Seitamaa-Hakkarainen, 2025; Lin et al., 2023). At the same time, maker settings can reproduce barriers when software, instructions, pace, or expectations assume prior technical competence (Bar-El & Worsley, 2021).

For special education, the critical question is therefore not whether VR or 3D printing is inherently effective, but how these technologies are organized into an accessible instructional pathway. Students may benefit when visual representations can be inspected and manipulated repeatedly, when tasks are broken into manageable steps, when peer and facilitator support are available, and when digital work leads to a tangible outcome with an authentic purpose. Such conditions are consistent with the broader special education technology literature, which emphasizes equitable access, instructional scaffolding, and learner participation (Cheng & Lai, 2020; Layachi & Pitchford, 2025; Lynch et al., 2024). The present study evaluates this type of pathway by integrating evidence from an interactive desktop 3D-modeling study and a related community digital-fabrication program.

1.1 Special Education Technology, VR, and Students With Autism Spectrum Disorder

Technology-supported learning for students with ASD has historically concentrated on social communication, behavior, and adaptive skills. These remain important targets, but the educational use of emerging technologies is broadening. JSET has published desktop-VR social learning with children with ASD (Ke et al., 2022), a K-12 review of VR interventions for students with disabilities (Carreon et al., 2022), a recent systematic review of VR applications for children with ASD (Fu et al., 2025), and design research examining what students with ASD and their teachers value in educational VR environments (Carreon et al., 2025). Recent practice-focused work also emphasizes sensory regulation, classroom integration, and individualized support when VR is used with students on the autism spectrum (Wagner et al.,

2026). Together, this literature supports a shift from asking whether VR is engaging to examining whether the interaction, support, and task design are educationally appropriate for particular students and goals.

Desktop-based 3D and nonimmersive virtual environments are particularly relevant to inclusive school contexts because they can provide interactive 3D visualization without requiring a head-mounted display. Students can remain visually connected to facilitators, peers, keyboards, mice, and physical reference materials. This may reduce equipment burden and create a predictable transition between digital and physical activity. Research on spatial learning also suggests that interactive 3D environments can be useful when students repeatedly rotate, inspect, resize, and align objects. Meta-analytic evidence indicates that virtual technologies can support spatial ability (Di & Zheng, 2022), and desktop virtual reality has shown particular benefits for learners with lower initial spatial ability (Lee & Wong, 2014). However, interaction must be aligned with the task because more complex interaction can also increase cognitive demands (Gittinger & Wiesche, 2024).

1.2 Digital Fabrication as Accessible Instructional Technology

Digital fabrication extends virtual interaction into tangible making. A student who rotates a digital model to inspect alignment is practicing a spatial operation; a student who then prints that model receives physical feedback about dimensions, fit, and design decisions. Repeated modeling can support imagination and technology-related interest (Lin et al., 2023), while open-ended prototyping can support technical skill and creativity (Soomro et al., 2025). For students with disabilities, however, the value of making depends on accessible participation. Inclusive maker research emphasizes visual demonstrations, sequenced instructions, repeated practice, accessible software, flexible facilitator support, and multiple ways to contribute (Bar-El & Worsley, 2021; Martin et al., 2020).

Research involving students with ASD suggests that interest-based making can reveal competencies that are not always visible in conventional instruction. Martin et al. (2020) reported gains in engineering-related self-efficacy and knowledge in an autism inclusion maker program. Murthi et al. (2024) similarly documented persistence, curiosity, and design activity among middle-school students with ASD using tools such as Tinkercad and 3D printing. These findings are important for special education technology because they position students as designers and producers rather than only as recipients of intervention. The present work builds on that perspective by following a sequence from virtual manipulation to digital modeling, physical fabrication, and public-facing product presentation.

1.3 Conceptual Framework: Accessible Technology-Supported Making

The study was guided by an accessible technology-supported making framework that integrates technology affordances with self-efficacy processes. Technology affordances describe the actions that an environment makes possible, such as viewing, manipulating, revising, sharing, and receiving feedback (Jeong & Hmelo-Silver, 2016). In the present context, visual orientation and viewpoint control were expected to support repeated spatial inspection; direct object manipulation was expected to support exploration and design refinement; 3D printing was expected to make digital decisions visible in a physical object; and peer support and authentic presentation were expected to provide social and motivational consequences for successful work.

Bandura's (1997) self-efficacy framework provides a complementary explanation for confidence. Successfully completing a model, solving a technical problem, producing a physical object, or helping a peer can function as mastery and social experiences that strengthen perceived capability. The framework therefore treats engagement, autonomy, and peer support as processes that may help sustain the practice needed for technical and spatial learning rather than as simple indicators that students liked the

technology. The proposed instructional pathway links accessible interaction and scaffolding with spatial practice, mastery experiences, technical skill, confidence, and authentic participation.

The two studies did not use the same participants or measures and were not combined statistically. Instead, they provide complementary evidence about different portions of the pathway. Table 1 summarizes the evaluation structure and the boundaries between the two datasets.

1.4 Purpose and Research Questions

The purpose of this multi-study evaluation was to examine whether an accessible sequence of virtual modeling and digital fabrication was associated with measurable changes in spatial, confidence, and applied-skill outcomes, and whether student experiences and program records were consistent with the proposed learning processes. Three research questions guided the analysis:

RQ1. In the desktop 3D-modeling study, what changes occurred in spatial ability and learning confidence among students with ASD, and what learning experiences help explain those changes?

RQ2. In the community digital-fabrication program, what changes occurred in understanding of 3D printing, 3D design skills, and the printing process among students with complete paired data?

RQ3. What implementation and authentic-application outcomes were documented across the broader seven-workshop program, and how do these outcomes converge with the quantitative and qualitative evidence?

2. Methodology

2.1 Design

A multi-study mixed-methods evaluation was used because the available evidence comprised two distinct but conceptually related datasets. Study 1 was a single-group pretest-posttest mixed-methods evaluation of interactive desktop 3D modeling with students with ASD. Study 2 was a community digital-fabrication program evaluation with a paired pretest-posttest subset and program-monitoring records. The evidence streams were analyzed separately and integrated only at the level of interpretation. No statistical pooling or cross-sample inferential comparison was conducted.

Table 1. Overview of the two complementary studies

Study	Design and participants	Primary outcomes and evidence
Study 1: Desktop 3D modeling	Single-group pretest-posttest mixed-methods evaluation; 30 students with ASD, aged 767-780 years	Spatial ability; learning confidence; interviews, observations, and facilitator field notes
Study 2: Digital fabrication	12-month community program across two special-needs settings; approximately 60 unique students; paired skills data for 19 participants	3D-printing understanding; 3D-design skills; printing-process understanding; program-monitoring records

Note. The datasets were analyzed separately and integrated only at the level of interpretation; no statistical pooling or cross-sample inferential comparison was conducted.

2.2 Study 1: Desktop 3D-Modeling Evaluation

2.2.1 Participants and Setting

Study 1 involved 30 students with autism spectrum disorder from a special-needs educational setting in Malaysia. Students were

10–15 years old, with 15 female and 15 male participants. School records indicated prior school-based screening and identification of ASD before study inclusion; the research team did not conduct a new clinical diagnostic assessment. Participants were selected purposively based on their school screening

status and ability to participate in computer-assisted learning activities. Parental or guardian consent was documented as an inclusion requirement in the study records.

2.2.2 Technology and Learning Activities

The intervention used a desktop-based 3D modeling environment on standard computers. Students constructed, rotated, resized, combined, aligned, and modified virtual objects. Activities progressed from guided demonstrations to increasingly independent design tasks. The environment was intended to make spatial transformations visible and reversible while allowing students to remain connected to peers and facilitators. The archive does not preserve the exact computer specifications or software versions used in every session; accordingly, the analysis emphasizes the interaction functions students used rather than hardware-specific claims.

2.2.3 Measures and Qualitative Evidence

Two pretest-posttest outcomes were available: spatial ability and learning confidence. Spatial ability was operationalized using a study-administered performance score that required students to visualize, transform, and reason about 3D objects and spatial relationships. Learning confidence represented perceived capability to understand and complete technology-supported 3D modeling tasks. The same measures were administered before and after the intervention. The archive preserves total-score descriptive statistics and inferential analyses, but not the exact instrument titles, developers, item counts, response formats, or item-level reliability output. Consequently, the measures are reported as study-specific outcomes rather than as standardized or norm-referenced instruments.

Qualitative evidence came from classroom observations, facilitator field notes, and semi-structured interviews collected during the same learning period. The archived analysis organized these data into five domains: attention and visual engagement, active exploration and creativity, learner autonomy and perceived competence, peer interaction and support, and emotional

engagement. The complete verbatim interview schedule was not retained, so the manuscript reports the recoverable domain structure and illustrative participant statements without reconstructing unverified questions. The archival record also did not preserve sufficient detail to verify the number of coders or any formal inter-coder agreement procedure; these procedures are therefore not reconstructed.

2.2.4 Data Analysis

The source analysis used descriptive statistics, Kolmogorov-Smirnov and Shapiro-Wilk tests of gain-score normality, paired-samples *t* tests, 95% confidence intervals for mean change, and paired-samples Cohen's *d_z*. The source calculated differences as pretest minus posttest, producing negative *t* values for improvements; that sign convention is retained in the table note. Qualitative data were analyzed thematically and then compared with quantitative outcomes through a joint-display logic. An archived descriptive table reported a spatial gain of 4.93, whereas the reported pretest and posttest means and the paired-test table imply a gain of 4.67. The internally consistent value of 4.67 is therefore used in the present manuscript.

2.3 Study 2: Community Digital-Fabrication Program

2.3.1 Participants and Program Context

Study 2 evaluated a 12-month community-engagement program implemented across two special-needs educational settings in northern Malaysia. Program monitoring records identify approximately 60 unique students aged 10–15 years, with female and male participation reported as balanced across the program cohort. Students had undergone school-based screening before recruitment. Available attendance documentation independently identifies 21 students in one workshop group and 20 students in another, providing a documented minimum of 41 named participants across the supplied rosters. Complete named attendance sheets were not available for all seven workshops, so the approximately 60-student figure is retained as the program-monitoring total rather than reconstructed from the partial rosters. Ninety

session attendances were recorded because some students attended multiple workshops.

Complete paired applied-skills data were available for 19 students from the program cohort. The archived analytic file did not retain participant-level age and sex identifiers for these 19 cases, so no subgroup analyses were attempted. Participant names and identity numbers from administrative rosters were not used in the outcome analyses and are not reported in this manuscript.

2.3.2 Program Sequence and Technologies

The seven workshops formed a staged digital-to-physical learning sequence. Students were

introduced to VR and 3D printing, learned 3D modeling with Tinkercad, received guided instruction in printer preparation and fabrication, refined designs into physical products, created digital promotional materials with Canva, and participated in social media and public-facing product presentation activities. Tinkercad and Canva are reported because they were the applications used in the program; the instructional principles are not dependent on these specific commercial products. Facilitators used short, sequenced instructions, visual demonstrations, hands-on repetition, and graduated independence to reduce barriers while preserving opportunities for choice and problem-solving.

Table 2. Instructional components across the seven-workshop digital-fabrication program

Program component	Student activity	Accessibility/scaffolding emphasis
Orientation	Introduction to VR and 3D printing	Visual demonstrations and short, sequenced instructions
3D modeling	Create and modify digital models in Tinkercad	Guided practice, repetition, and gradual independence
Printer preparation	Prepare models and learn fabrication procedures	Hands-on facilitator support and stepwise practice
Product refinement	Revise designs and produce physical objects	Visible feedback from printed outcomes and problem-solving
Digital promotion	Create promotional materials in Canva	Structured templates and opportunities for choice
Public presentation	Branding, pricing, online promotion, and product presentation	Authentic audience and supported participation

Note. These components describe the staged learning sequence documented across seven workshops; they are not presented as a one-to-one mapping of individual workshops.

2.3.3 Applied-Skills Measure and Psychometric Reconstruction

A project-developed pretest-posttest questionnaire was used as a criterion-referenced program measure. Archived item output shows 20 items across four sections: 3D-printing understanding (4 items), 3D-design skills (7

items), printing-process understanding (6 items), and workshop perceptions (3 items). The three skill sections were the outcomes of interest. Items addressed include, for example, understanding what 3D printing is and how it is used; the ability to use 3D design software and design objects independently; understanding design steps; confidence in using the software;

understanding how a 3D printer produces an object; and understanding the relationship between a digital design and its printed output. The questionnaire was administered in Malay and aligned directly with workshop objectives.

The original questionnaire form and formal adaptation record were not retained. Archived item outputs show responses predominantly in the 1–4 range, although one posttest response of 5 appears in a printing-process item; therefore, the exact response anchors are not reconstructed. Domain means are reported exactly as archived. Internal consistency was not

reported in the original project file. However, approximate Cronbach's alpha values could be reconstructed from the archived item variances and composite-score variances because each domain score was the mean of its items. The resulting estimates were .76 at pretest and .68 at posttest for 3D-printing understanding, .89 and .79 for 3D-design skills, and .90 and .70 for printing-process understanding. These estimates are approximate because the archived item standard deviations were rounded and should not be treated as a substitute for raw-data psychometric analysis.

Table 3. Reconstructed internal consistency estimates for Study 2 skill domains

Skill domain	Items	Pretest α	Posttest α
3D-printing understanding	4	.76	.68
3D-design skills	7	.89	.79
Printing-process understanding	6	.90	.70

Note. Alpha values were reconstructed from archived item variances and composite-score variances and are approximate because archived item standard deviations were rounded.

2.3.4 Data Analysis and Program-Monitoring Evidence

Archived analyses reported paired-samples *t* tests for the three skill domains. Cohen's d_z was reconstructed from each paired *t* statistic using $d_z = |t|/\sqrt{n}$, and 95% confidence intervals for mean changes were reconstructed from the reported mean differences and standard errors. Participant-level raw responses were not retained, so the normality of paired difference scores could not be independently reassessed for the $n = 19$ analytic subset; this limitation is considered when interpreting the inferential results. Program-monitoring evidence included attendance records, workshop reports, design portfolios, photographs, product samples, and records of product presentation and sales. These implementation indicators were analyzed descriptively and were not treated as equivalent to psychometric learning outcomes.

2.4 Ethical Considerations

Study 1 was conducted in accordance with the Declaration of Helsinki and received approval from the Human Research Ethics Committee of (Hidden Name), protocol USM/JEPeM/PP/26020171. Informed consent for participation was obtained from parents or legal guardians and documented in the study records. Study 2 used de-identified program-evaluation records for the present secondary analysis. No participant names, identity numbers, or contact details were included in the research dataset.

3. Results

3.1 Study 1: Spatial Ability and Learning Confidence

Spatial ability increased from $M = 44.83$ ($SD = 7.41$) at pretest to $M = 49.50$ ($SD = 8.69$) at posttest. The paired comparison was statistically significant, $t(29) = -3.43$, $p = .002$, with a

moderate paired-samples effect size, $d_z = 0.63$. The mean increase was 4.67 points, 95% CI [1.89, 7.45]. Learning confidence increased from $M = 45.37$ ($SD = 6.32$) to $M = 48.47$ ($SD = 7.82$), $t(29) = -2.73$, $p = .011$, $d_z = 0.50$; the mean

increase was 3.10 points, 95% CI [0.78, 5.42]. Normality tests reported in the source analysis were nonsignificant for both gain-score distributions, supporting the paired t-test analyses.

Table 4. Study 1 pretest-posttest outcomes (n = 30)

Outcome	Pretest M (SD)	Posttest M (SD)	Mean increase	t(29)	p	d _z
Spatial ability	44.83 (7.41)	49.50 (8.69)	4.67	-3.43	.002	0.63
Learning confidence	45.37 (6.32)	48.47 (7.82)	3.10	-2.73	.011	0.50

Note. The archived analysis defined differences as pretest minus posttest; therefore, negative t values indicate higher posttest scores. Cohen's d_z denotes the standardized mean change for paired observations. The 95% confidence intervals for mean increases are reported in the text.

3.2 Study 1: Learning Experiences

The qualitative findings provide process evidence that helps interpret the pretest-posttest changes. First, students described the 3D environment as visually engaging and reported that multiple viewing angles supported focus and understanding. One student explained, "I can see the object clearly from all angles, so it attracts my interest and helps me focus." Observations documented sustained rotation, resizing, viewpoint comparison, and inspection during modeling tasks. These behaviors are consistent with repeated spatial practice rather than passive exposure to 3D content.

Second, students engaged in active exploration. They modified shapes, combined objects, tested alternatives, and sometimes extended tasks beyond the examples provided. This pattern suggests that open-ended manipulation created repeated opportunities for spatial problem-solving and design decision-making. Third, students described increasing autonomy. They

attempted solutions before requesting help and expressed satisfaction when they completed designs independently. These mastery experiences are consistent with the moderate increase in learning confidence.

Fourth, peer interaction was a recurring part of the learning process. Students exchanged modeling strategies, demonstrated software functions, and helped classmates solve technical problems. Peer teaching provided a way to participate socially through a shared artifact and also gave students opportunities to demonstrate competence. Finally, positive emotional engagement supported persistence. Students generally described the activities as enjoyable and continued working despite occasional software or alignment difficulties. The qualitative evidence does not establish causal mediation, but it converges with the proposed pathway from visual manipulation and mastery to spatial practice and confidence.

Table 5. Qualitative learning-experience domains in Study 1

Domain	Observed or reported pattern	Relation to proposed learning process
Attention and visual engagement	Sustained viewing, rotation, resizing, and comparison of multiple angles	Repeated spatial inspection and focused practice

Domain	Observed or reported pattern	Relation to proposed learning process
Active exploration and creativity	Modification, combination, and testing of alternative shapes and designs	Spatial problem-solving and design decision-making
Autonomy and perceived competence	Attempting solutions independently before requesting help	Mastery experiences and learning confidence
Peer interaction and support	Sharing strategies, demonstrating functions, and troubleshooting for classmates	Social participation and opportunities to demonstrate competence
Emotional engagement	Enjoyment and persistence despite software or alignment difficulties	Sustained participation and task persistence

Note. The qualitative evidence is interpretive process evidence and does not establish causal mediation.

3.3 Study 2: Applied Digital-Fabrication Skills

All three paired skill outcomes improved significantly. Understanding of 3D printing increased from $M = 2.3421$ ($SD = 0.5665$) to $M = 3.2105$ ($SD = 0.5087$), $t(18) = -5.752$, $p < .001$, $d_z = 1.32$. 3D-design skills increased from $M = 2.4436$ ($SD = 0.7632$) to $M = 3.0451$ ($SD =$

0.5041), $t(18) = -3.557$, $p = .002$, $d_z = 0.82$. Printing-process understanding increased from $M = 2.3333$ ($SD = 0.7515$) to $M = 3.1579$ ($SD = 0.4631$), $t(18) = -4.592$, $p < .001$, $d_z = 1.05$. The effect-size estimates are large, but they should be interpreted as within-sample change in program-specific competencies rather than as causal treatment effects.

Table 6. Study 2 paired applied-skill outcomes (n = 19)

Outcome	Pretest M (SD)	Posttest M (SD)	t(18)	p	d _z
3D-printing understanding	2.3421 (0.5665)	3.2105 (0.5087)	-5.752	< .001	1.32
3D-design skills	2.4436 (0.7632)	3.0451 (0.5041)	-3.557	.002	0.82
Printing-process understanding	2.3333 (0.7515)	3.1579 (0.4631)	-4.592	< .001	1.05

Note. Cohen's $d_z = |t| / \sqrt{n}$. The 95% CIs for mean increases were [0.55, 1.19], [0.25, 0.96], and [0.45, 1.20], respectively. Effects represent within-sample change, not causal treatment effects.

3.4 Program Implementation and Authentic Application

Program records show that seven structured workshops were delivered and approximately 60 unique students participated across the two settings. The 90 recorded session attendances reflect repeated participation rather than 90 unique students. More than 10 original printable designs were documented, and 40 3D-printed products were produced and commercialized

during the program period. Students also created promotional materials and were introduced to branding, pricing, online promotion, and public-facing product presentation. These indicators do not establish sustained entrepreneurship or employment outcomes. Their educational significance lies in students moving from screen-based representations to tangible products intended for an audience beyond the immediate instructional exercise.

Implementation records also show that environmental conditions shaped access. Printer location, computer performance, session continuity, and the availability of facilitator support affected participation. Some early designs required revision before printing or presentation. These challenges are important findings in special education technology because they show that accessibility depends on organizational and instructional conditions as well as on the interface itself.

4. Discussion

4.1 Integrated Interpretation

Across the two studies, the strongest convergence occurred around three processes. First, repeated visual manipulation was consistent with improved spatial performance and better understanding of digital design. Second, scaffolded practice and visible mastery were consistent with gains in confidence and program-specific skill. Third, the transition from a digital model to a physical artifact amplified the consequences of design decisions and provided a compelling reason to refine the work. The evidence therefore supports an instructional interpretation in which accessible interaction, structured support, and meaningful production work together. It does not support a single pooled program effect because the samples, measures, and study purposes were different.

4.2 Contribution to Special Education Technology

The central contribution of this study is a special education technology pathway rather than evidence for one isolated tool. Students interacted with 3D representations, manipulated designs, fabricated objects, solved problems with peers, and moved toward authentic presentation. The quantitative and qualitative results suggest that these stages can support cognitive, applied, and affective outcomes when they are intentionally scaffolded. This interpretation is consistent with JSET's recent emphasis on moving emerging technologies from innovation toward meaningful classroom integration (Carreon et al., 2026; Wagner et al., 2026).

The findings also connect with the broader literature on virtual and interactive 3D learning in special education. JSET reviews have shown that VR research for students with disabilities spans a wide range of immersion levels and educational targets (Carreon et al., 2022; Fu et al., 2025). Study 1 is reported here as interactive desktop 3D modeling rather than as a hardware-defined VR intervention because the archived materials do not preserve sufficient technical detail to verify a specific VR configuration. The present results suggest that an interactive desktop 3D system can be educationally useful when the task requires repeated object manipulation and when students benefit from maintaining visual access to peers, facilitators, and physical materials. These findings do not establish that desktop 3D modeling is superior to immersive VR; instead, they support matching the interaction format to the learning goal and learner context, a principle that also emerges from user-centered VR design research (Carreon et al., 2025).

Evidence from adjacent educational technology contexts similarly emphasizes the role of pedagogical design rather than technology alone. In design education, AI-generated virtual instructors increased affective engagement, while a conversational teaching style improved academic performance, reduced cognitive load, and supported engagement (Chen, Mokmin, Shen, et al., 2025). In middle-school history, a generative AI-supported arts-based learning approach improved historical knowledge and motivation while reducing cognitive load (Chen, Mokmin, & Shen, 2025). Although these studies involved different technologies and learner populations, they reinforce the present interpretation that emerging tools are most productive when embedded in structured, learner-centered instructional designs.

4.3 Spatial and Technical Learning Through Visible Manipulation

The moderate improvement in spatial ability in Study 1 is consistent with the actual interaction demands of 3D modeling. Students repeatedly rotated, resized, aligned, combined, and

inspected objects. These operations externalized spatial transformations and gave students opportunities to compare an intended design with a visible result. This is consistent with desktop-VR evidence showing benefits for spatial learning (Lee & Wong, 2014) and with meta-analytic evidence that spatial skills can be trained in virtual environments (Di & Zheng, 2022). The large changes in the Study 2 skill domains extend the argument from spatial cognition to applied production. Students not only learned what a printer was; they learned design steps, software use, and the relationship between a digital file and a physical object.

The digital-to-physical transition is especially important for special education technology. A virtual model can be adjusted without consequence, whereas a printed object reveals whether dimensions, alignment, and form work in practice. This visible feedback can make abstract design decisions more concrete. Prior work in special education has highlighted the potential of 3D printing for accessible learning materials and participation (Buehler et al., 2014), while broader maker research shows that iterative modeling can support imagination and technical interest (Lin et al., 2023). The present program suggests that students with disabilities can participate in this full design cycle when entry barriers are reduced through modeling demonstrations, short instructions, repeated practice, and facilitator support.

4.4 Confidence, Agency, and Peer Participation

Learning confidence improved moderately in Study 1, and the qualitative data provide a plausible explanation. Students described independent problem-solving, persistence, and pride in successful designs, while observations revealed peer teaching and reciprocal assistance. These experiences align with Bandura's (1997) account of self-efficacy, in which mastery and social feedback contribute to perceived capability. Similar processes have been reported in inclusive maker programs for students with ASD, in which engineering self-efficacy, interest, persistence, and peer communication can

develop through interest-driven projects (Martin et al., 2020; Murthi et al., 2024).

For special educators, peer support is important because it broadens what counts as participation. Students who may find highly verbal classroom interactions difficult can contribute by sharing an artifact, demonstrating a software function, troubleshooting a design, or showing another student how to complete a step. The technology therefore becomes a context for participation rather than an end in itself. This perspective is compatible with JSET's emphasis on technologies that improve outcomes for students with disabilities and with current VR guidance that foregrounds individualized support and classroom integration (Wagner et al., 2026).

A related special-education study using augmented reality in physical education for students with dyslexia also highlighted the importance of designing technology around learner needs and implementation conditions, including resource availability and teacher support (Mokmin et al., 2025). Although the instructional domain differs from digital fabrication, the study supports the broader principle that inclusive educational technology depends on accessible design, scaffolding, and contextual support rather than the technology itself.

4.5 Implications for Special Education Practice

Five practical implications follow from the findings. First, special educators should select the interaction format based on instructional need rather than assuming that head-mounted immersion is always preferable. Desktop 3D environments may be advantageous when students need continuous access to facilitator cues, peers, or physical materials. Second, the interaction should be tied to a consequential task. Rotation, scaling, and viewpoint control become more meaningful when students use them to prepare a model for fabrication rather than as decontextualized software exercises.

Third, instruction should progress from demonstration to guided practice and then to increasing independence. The baseline data in

Study 2 showed low prior familiarity with 3D printing and design software, so immediate independent use would likely have created unnecessary barriers. Fourth, peer assistance should be designed as a legitimate part of the learning environment. Structured opportunities to compare designs, explain procedures, and troubleshoot together can support both technical learning and participation. Fifth, authentic products can provide a motivating endpoint, but educators should distinguish educational authenticity from claims about entrepreneurship. In this study, product presentation and short-term sales showed that students could move from design to audience; they do not establish long-term economic outcomes.

4.6 Limitations

Several limitations constrain interpretation. Both quantitative components used one-group pretest-posttest designs without comparison conditions. Maturation, repeated testing, instructor effects, and other alternative explanations therefore cannot be ruled out. Study 1 involved 30 students with ASD from a single special-needs educational setting, and Study 2 included only 19 students who completed paired questionnaires. The limited sample sizes constrain generalizability and statistical precision. In addition, the two datasets were separate. Their results can be interpreted together conceptually, but they do not estimate a single overall program effect.

Measurement documentation is another limitation. Study 1's archive did not retain the exact titles, item structures, adaptation histories, or reliability coefficients for the spatial-ability and confidence measures. Study 2 provided stronger recoverable item-level summary information, which allowed approximate internal consistency coefficients to be reconstructed, but raw responses were unavailable, and the exact response anchors could not be verified. These limitations are reported rather than replaced with assumed instrument information. Future work should prospectively retain complete instrument manuals, item-level data, content-validation records, and reliability estimates. The absence of

participant-level raw responses in Study 2 also prevented an independent reassessment of the distribution of paired difference scores and limited additional sensitivity analyses.

Program-level attendance documentation was also incomplete. Two available rosters verified 41 named students, while project monitoring reported approximately 60 unique beneficiaries. Because complete attendance sheets were not retained for every workshop, individual intervention dose across all seven sessions could not be reconstructed. Finally, outcomes were measured immediately after the learning activities. The study did not test long-term retention, generalization to other academic tasks, or sustained independent use of digital fabrication technologies.

4.7 Directions for Future Research

Future studies should use comparison conditions or staggered implementation designs, report intervention dose at the individual level, and include follow-up assessments. Research should also compare interaction formats, such as desktop versus immersive VR, while controlling for task structure and instructional support. For students with disabilities, outcomes should extend beyond achievement to include accessibility, autonomy, persistence, peer participation, and transfer of technology skills. Most importantly, future digital-fabrication studies should use psychometrically documented measures and preserve raw item-level data so that reliability, measurement invariance, and subgroup patterns can be evaluated directly.

5. Conclusion

This multi-study evaluation suggests that students with disabilities can engage productively with advanced digital-fabrication technologies when instruction is organized as an accessible progression from virtual exploration to physical making. Across separate samples, students showed improvements in spatial ability, learning confidence, understanding of 3D printing, design skills, and understanding of the printing process. Interviews, observations, and program records converged on the importance of repeated visual manipulation, scaffolded practice, mastery, peer

support, and authentic product creation as learning processes. The findings do not establish a causal program effect. However, they show how desktop 3D modeling and 3D printing can be integrated as instructional technologies that support participation and competence in special education. The stronger implication is not that a particular tool should be adopted, but that emerging technologies should be designed around accessible interaction, purposeful tasks, and opportunities for students to become active creators.

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7. Author Declaration

7.1 Originality and Conflicts of Interest

The manuscript is submitted as original work. The authors declare no competing interests.

7.2 Ethics Approval

Study 1 was conducted in accordance with the Declaration of Helsinki and approved by the Human Research Ethics Committee of Universiti Sains Malaysia (JEPeM-USM), protocol USM/JEPeM/PP/26020171.

7.3 Data Availability

De-identified data supporting the findings are available from the corresponding author upon reasonable request, subject to participant confidentiality, ethical approval, and institutional data-governance requirements. Author-contribution and funding details are provided separately in the title page and submission metadata to preserve double-anonymized review.

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