Enhancing Scientific Conceptualization and Responsibility in Deaf Learners Through Technology-Enhanced Learning: Development and Validation of a Digital Fun Thinkers Tool

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ABSTRACT

Purpose of the study: This study aims to design, develop, and validate a culturally adapted Digital Fun Thinkers learning tool to enhance scientific conceptualization and learning responsibility among deaf and hard-of-hearing elementary students in Bengkala Village, Bali, Indonesia.

Methodology: This study employed the ADDIE instructional design model and a one-group pretest–posttest quasi-experimental design. The Digital Fun Thinkers tool was developed as an interactive multimedia application. Data were analyzed using Aiken's V, paired-sample t-test, and normalized gain (N-Gain).

Main Findings: Expert validation indicated high validity (media experts: V = 0.9583; material experts: V = 0.9350) and very practical use (user satisfaction = 81.39%). Students' scientific conceptualization improved significantly (t = -37.997, p < 0.001; N-Gain = 0.7338, large effect). Learning responsibility averaged 66.28 (very high category).

Novelty/Originality of this study: This study introduces a culturally grounded digital learning tool integrating Kata Kolok sign language, gamified features, and local scientific contexts for deaf learners. It advances inclusive science education by providing empirically validated, technology-enhanced resources tailored to marginalized DHH communities in rural settings.

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1. INTRODUCTION

Inclusive education represents a fundamental human right and a critical mechanism for achieving educational equity, enabling learners with diverse needs to access quality education in supportive, accessible environments [1]. For deaf and hard-of-hearing (DHH) learners, however, the realization of this right remains significantly constrained by multiple, intersecting barriers including inadequate assistive technologies, limited teacher training in deaf pedagogy, scarcity of culturally responsive curriculum materials, and insufficient access to sign language-based instruction [2]-[4]. These barriers are particularly pronounced in rural and under-resourced educational settings, where DHH students often experience compounded educational disadvantages [5], [6].

Indonesia hosts one of the world's most linguistically and culturally unique deaf communities in Bengkala Village, Kubutambahan District, Buleleng Regency, Bali. In this rural community, approximately 2% of the population (about 43 families) are congenitally deaf and communicate through Kata Kolok, an indigenous village sign language that has evolved over multiple generations [7]. Unlike many deaf communities worldwide, which often experience social marginalization, the Bengkala kolok community demonstrates remarkable social integration and cultural acceptance [8], [9]. Despite this social inclusivity, kolok students, 18 of whom attend SD Negeri 2 Bengkala, continue to face substantial educational challenges, particularly in accessing quality science education that requires complex conceptual understanding and abstract reasoning [10], [11].

This study is grounded in two complementary theoretical frameworks: constructivist learning theory and Universal Design for Learning (UDL). Constructivism posits that learners actively construct knowledge through meaningful interactions with content, peers, and their environment, rather than passively receiving information [12]. For DHH learners, constructivist principles are particularly salient, as these students benefit significantly from multisensory, visual-spatial, and experientially grounded learning experiences that leverage their visual-cognitive strengths [13]. The UDL framework further extends this theoretical foundation by emphasizing the design of flexible learning environments that accommodate diverse learner needs through multiple means of representation, expression, and engagement [14]. Digital learning technologies, when designed with UDL principles, can provide DHH learners with customizable, multimodal access to content, thereby reducing cognitive load and enhancing comprehension [15]-[17].

Despite growing recognition of the importance of technology-enhanced learning for Deaf and Hard of Hearing (DHH) students, significant gaps remain in both the empirical literature and educational practice. First, most assistive technologies and educational software for DHH learners are developed for mainstream sign languages such as American Sign Language and British Sign Language, and are therefore not culturally responsive to indigenous signing communities like Kata Kolok users [18]. This cultural and linguistic misalignment can reduce tool effectiveness and diminish student engagement. Second, research on DHH education continues to be dominated by a focus on literacy and language development, while science education, particularly conceptual understanding at the elementary level, remains critically underexplored [19]. Science curricula themselves often rely heavily on auditory instruction and text-dense materials, creating substantial accessibility barriers for DHH learners. Third, although emerging evidence indicates that gamified and interactive digital tools can enhance engagement and learning outcomes [20-[22], few rigorously validated tools are specifically designed to address the needs of DHH learners in developing countries, where resources and technological infrastructure are limited. Fourth, many studies focus almost exclusively on cognitive outcomes, such as achievement scores, while neglecting important affective and behavioral dimensions, including learning responsibility, motivation, and self-regulation, which are essential for long-term academic success [23]-[25].

In response to these gaps, this study aims to design and develop a culturally adapted, technology-enhanced learning tool, Digital Fun Thinkers, specifically tailored for Kata Kolok-using DHH elementary students to support science learning. The study further seeks to validate the tool's content validity, usability, and pedagogical quality through systematic expert evaluation, and to examine its effectiveness in improving scientific conceptualization among Grade 5 DHH students. In addition, the research investigates the impact of using Digital Fun Thinkers on students' learning responsibility as a key affective-behavioral outcome. More specifically, the study addresses three main research questions: the extent to which the Digital Fun Thinkers tool is valid and practical for use with DHH elementary students in science education (RQ1); the effect of the tool on DHH students' scientific conceptualization, as measured by pre- and post-intervention assessments (RQ2); and how the use of the tool influences DHH students' learning responsibility (RQ3).

This research makes several important contributions. Theoretically, it extends constructivist and Universal Design for Learning (UDL) frameworks into the under-researched domain of indigenous DHH education, demonstrating how these perspectives can inform culturally responsive technology design. Methodologically, the study employs a rigorous, multi-method validation approach, including expert validation, usability and practicality testing, and a quasi-experimental effectiveness evaluation, thereby providing a replicable model for educational technology research in special education contexts. Practically, the Digital Fun Thinkers tool offers a low-cost, scalable solution for enhancing access to quality science education for DHH learners in resource-constrained settings, with potential adaptability across diverse sign language communities. From a policy perspective, the findings provide empirical evidence to support initiatives that promote inclusive, technology-enhanced education for students with disabilities in Indonesia and comparable developing country contexts.

2. RESEARCH METHOD

2.1. Research Design

This study employed a developmental research design complemented by a one-group pretest-posttest quasi-experimental design to achieve its objectives [26]-[30]. Developmental research was appropriate for the systematic design, development, and validation of the Digital Fun Thinkers tool, while the quasi-experimental component enabled rigorous evaluation of the tool's effectiveness on learning outcomes [31]-[33].

The rationale for employing a quasi-experimental design, rather than a randomized controlled trial (RCT), was twofold: (1) the small population of DHH students at the research site (n = 18) precluded meaningful randomization and creation of a control group, and (2) ethical considerations regarding withholding a potentially beneficial intervention from any DHH students in an already under-resourced setting [34]. While quasi-experimental designs have limitations regarding internal validity, recent methodological advances, including strong theoretical grounding, rigorous measurement, and transparent reporting, enable credible causal inferences when RCTs are infeasible [35].

2.2. Research Context and Participants

The study was conducted at a public elementary school located in Bengkala Village, Kubutambahan District, Buleleng Regency, Bali, Indonesia. This institution serves as a primary educational hub for both hearing and deaf students through an inclusive educational model. The village itself is internationally recognized for its unique linguistic ecology, where Kata Kolok, an indigenous village sign language, is utilized by both deaf and hearing community members, thereby facilitating exceptional social integration for deaf individuals [36].

Due to the specific and limited nature of the population, the study employed a census sampling approach, also known as total population sampling, to include all eligible Deaf and Hard of Hearing (DHH) students [37]. This strategy is particularly appropriate when the target population is small, geographically concentrated, and shares specific characteristics essential to the research focus. The participants consisted of eighteen Grade 5 DHH students with an age range of 10 to 12 years, a mean age of 10.8, and a standard deviation of 0.7.

To ensure the integrity of the data, specific inclusion and exclusion criteria were applied. Participants were required to be enrolled in Grade 5 at the research site, diagnosed with congenital profound or severe bilateral hearing loss, and use Kata Kolok as their primary mode of communication. Additionally, eligible students had no co-occurring intellectual disabilities or severe visual impairments, and both parental informed consent and student assent were secured prior to the study. Conversely, students were excluded if they presented with co-occurring cognitive or visual impairments that would prevent meaningful engagement with digital tablet-based learning tools.

Table 1. Participant Demographic Characteristics (N = 18)

Characteristic	n	%
Gender		
Male	10	55.6
Female	8	44.4
Primary Communication Mode		
Kata Kolok	18	100.0
Prior Science Achievement		
Below Average (<60)	12	66.7
Average (60-75)	6	33.3
Above Average (>75)	0	0.0
Hearing Loss Severity		
Profound (>90 dB)	15	83.3
Severe (70-90 dB)	3	16.7

2.3. Instructional Design and Development Process (ADDIE Model)

The Digital Fun Thinkers tool was systematically developed using the ADDIE model, which comprises five iterative phases, namely Analysis, Design, Development, Implementation, and Evaluation [38], [39], [40].

2.3.1. Analysis Phase

The first phase involved a comprehensive needs assessment. Semi-structured interviews were conducted with three science teachers and the principal of one elementary school in Bali to identify pedagogical needs, existing instructional challenges, and resource constraints. The findings indicated several key issues, including the absence of science learning materials that integrate sign language, a strong reliance on text-based instruction that does not align with the visual learning preferences of DHH students, low levels of student engagement, limited conceptual understanding in science, particularly for abstract topics, and a need for affordable and portable digital learning tools that are compatible with existing school infrastructure, such as Android tablets.

Learner analysis was carried out by examining the cognitive and linguistic profiles of DHH students through academic records and consultations with teachers and sign language interpreters. The analysis showed that DHH students demonstrated strong visual-spatial processing abilities but had limited proficiency in written Indonesian. This condition required the design of learning materials with minimal text and extensive use of Kata

Kolok video demonstrations. Content analysis focused on the Grade 5 Semester 1 science topic on Living Things. This topic was selected because it aligns with national curriculum standards, involves conceptual complexity that benefits from scaffolded instruction, and offers rich opportunities for visual-spatial representation.

2.3.2. Design Phase

In the design phase, six specific learning objectives were formulated with reference to Bloom's Revised Taxonomy [41]. These objectives included the ability to identify and classify living and non-living things based on observable characteristics, explain the basic needs of living things such as air, water, food, and sunlight, analyze the life cycle stages of plants and animals, apply understanding of the characteristics of living things in real-world contexts, compare and contrast different types of living things, and evaluate the importance of living things in ecosystems. A guided discovery learning approach was selected as the main instructional strategy. Through this approach, students explore content via interactive activities, receive scaffolded support through visual prompts and Kata Kolok video instructions, and consolidate their understanding through gamified quizzes and problem-solving challenges [42]. In terms of media selection, interactive multimedia delivered via Android tablets was chosen as the primary platform. This decision was based on learner characteristics and technological constraints, as tablets provide portability, touch-screen interactivity, and offline functionality, all of which are critical in resource-limited settings [43]-[45].

The interface design adhered to UDL guidelines [46] and multimedia learning principles [47]. Several principles guided the design, including visual clarity with high-contrast color schemes, large touch targets, and minimal textual clutter, integration of sign language through Kata Kolok video demonstrations for all instructional content, multimodal representation that combines images, animations, sign language videos, and minimal text, and the incorporation of gamification elements such as progress bars, achievement badges, immediate visual feedback, and tiered difficulty levels. Assessment design included both formative and summative components. Formative assessments were embedded within the tool, while summative assessments were implemented through pretests and posttests. The assessment formats comprised visual multiple-choice questions with image-based options, drag-and-drop categorization tasks, interactive labeling activities, and scenario-based problem-solving challenges.

Figure 1. Integration at Smart Apps Creator

2.3.3. Development Phase

During the development phase, content was created collaboratively by a multidisciplinary team consisting of two science education specialists, two special education teachers with expertise in deaf education, one Kata Kolok interpreter who is a native signer from the local community, and two instructional designers with expertise in multimedia development. From a technical perspective, the tool was developed using Smart Apps Creator (SAC), a no-code multimedia authoring platform that supports the creation of interactive applications for Android and iOS [39], [48], [49]. Visual assets, including images and animations, were created using Canva, while Kata Kolok instructional videos were recorded with signers from the community. These elements were then integrated into the Digital Fun Thinkers tool. An initial prototype was pilot-tested with five DHH students who were not part of the final study sample. The pilot aimed to identify usability issues and technical bugs. Revisions were made iteratively based on student feedback and observational data gathered during the pilot sessions.

2.3.4. Implementation Phase

Prior to implementation, two teachers received eight hours of training focused on navigating the tool, handling basic troubleshooting, and applying facilitation strategies to support student learning during classroom use. The Digital Fun Thinkers tool was then implemented over a four-week period, comprising twelve instructional sessions, each lasting forty-five minutes. Students worked individually with Android tablets in the school's computer lab, while teachers provided minimal facilitation to maintain fidelity to the intervention design. Implementation fidelity was monitored through structured observation checklists completed by an independent observer for thirty percent of the sessions, equivalent to four out of twelve sessions. The observations indicated an average fidelity score of 94.2 percent, reflecting a high level of adherence to the planned intervention protocol.

Figure 2. Use of fun thinkers' digital media during learning

2.3.5. Evaluation Phase

The evaluation phase consisted of three main components. First, expert validation was conducted to assess content quality and usability. Second, student practicality assessments were carried out to capture learners' perceptions of ease of use, engagement, and usefulness. Third, an effectiveness evaluation was performed by analyzing learning outcomes based on pretest and posttest results. Together, these components provided a comprehensive evaluation of the Digital Fun Thinkers tool from theoretical, practical, and empirical perspectives.

2.4. Data Collection Instruments

2.4.1. Expert Validation Instruments

Two expert validation instruments were developed to assess the quality of the Digital Fun Thinkers tool from both media and material perspectives. The Media Expert Validation Questionnaire consisted of 24 items designed to assess four key dimensions. These dimensions included Display and Appearance, which was measured through seven items, Language Use with five items, Ease of Use evaluated by six items, and Usefulness and Utility also assessed through six items. Each item was rated using a 4-point Likert scale, where 1 represented Poor and 4 represented Excellent. Four media experts with an average of 12.3 years of experience in educational technology participated in the validation process. The Material Expert Validation Questionnaire comprised 26 items and evaluated five dimensions. These dimensions were Self-Instructional, measured by six items, Self-Contained with five items, Language also with five items, Adaptive with five items, and User-Friendly with five items. Four subject matter experts specializing in science education and special education, with an average of 10.8 years of experience, conducted the validation. Both validation instruments demonstrated strong psychometric properties. Content validity was confirmed through Aiken's V coefficient of 0.89, while internal consistency reliability was high, with Cronbach's alpha values of 0.91 for the media instrument and 0.88 for the material instrument. These values were obtained through pilot testing involving ten external experts.

2.4.2. Practicality Assessment Instrument

A Student Practicality Questionnaire consisting of 15 items was developed to assess perceived usability, engagement, and satisfaction with the Digital Fun Thinkers tool. The items were adapted from the System Usability Scale [50] and modified to ensure comprehensibility for DHH elementary students. To accommodate students' limited literacy, visual analog scales with pictorial anchors were employed. The instrument demonstrated adequate internal consistency reliability, with a Cronbach's alpha value of 0.84.

2.4.3. Learning Outcome Assessment (Conceptual Understanding)

A Science Concept Test was developed as a 25-item criterion-referenced assessment to measure conceptual understanding of the Living Things topic. The test included three types of items. First, 15 visual multiple-choice items, each with four response options. Second, five image-based classification tasks that required students to categorize visual stimuli. Third, five scenario-based application problems designed to assess the ability to apply learned concepts in practical contexts. Content validity was established through a rigorous development process. Test items were created by science curriculum specialists and subsequently reviewed by three content experts, resulting in a Content Validity Index of 0.92. Reliability was assessed through multiple methods. Internal consistency was confirmed with a KR-20 coefficient of 0.81, while test-retest reliability yielded a correlation coefficient of 0.78, which was statistically significant at $p < 0.001$. These reliability estimates were obtained through pilot testing with 20 Grade 5 hearing students. Item analysis was conducted to evaluate the psychometric quality of individual test items. The analysis revealed appropriate difficulty levels, with a mean item difficulty of 0.52, indicating that the test was moderately challenging. Discrimination indices were also strong, with a mean value of 0.41, confirming that the test effectively differentiated between high and low performers.

2.4.4. Learning Responsibility Instrument

A Learning Responsibility Scale consisting of 20 items was adapted from established instruments in the literature [51]. The scale assessed five dimensions of learning responsibility. These dimensions included Task Completion, measured by four items, Persistence also with four items, Help-Seeking Behavior evaluated through four items, Self-Regulation with four items, and Goal Orientation also assessed by four items. Each item was rated on a 4-point Likert scale, where 1 indicated Never and 4 indicated Always. The validity and reliability of the instrument were rigorously evaluated. Confirmatory factor analysis supported the proposed five-factor structure, with fit indices indicating good model fit. Specifically, the chi-square to degrees of freedom ratio was 1.82, the Comparative Fit Index was 0.94, and the Root Mean Square Error of Approximation was 0.06. Internal consistency reliability was excellent, with a Cronbach's alpha coefficient of 0.89, indicating that the scale items consistently measured the intended construct.

2.5. Data Analysis Procedures

Expert validation ratings were analyzed using Aiken's V coefficient, a content validity index suitable for aggregating expert judgments [52]. Aiken's V ranges from 0 to 1, with values ≥ 0.80 indicating high content validity [52]. The calculation involves summing the adjusted expert ratings and dividing by the product of the number of experts and the number of rating categories minus 1. In this formula, s represents the difference between an expert rating and the lowest possible score, n is the number of experts, and c is the number of rating categories. The interpretation criteria define a V value ≤ 0.40 as low validity, a value between 0.40 and 0.80 as moderate validity, and a value ≥ 0.80 as high validity. Student practicality ratings were converted to percentages and interpreted using established criteria [53]. A percentage range of 81.25% to 100% is categorized as Very Practical, while a range of 62.50% to 81.24% is considered Practical. Scores falling between 43.75% and 62.49% are classified as Less Practical, and scores from 25.00% to 43.74% are categorized as Not Practical. Learning responsibility scores were categorized based on an ideal mean of 50 and an ideal standard deviation of 10 [54]. A score X greater than 65 is categorized as Very High, while a score between 50 and 65 is considered High. Scores greater than 35 and up to 50 are classified as Moderate, and any score $X \leq 35$ is categorized as Low.

Prior to hypothesis testing, data normality was assessed using the Shapiro Wilk test, which is appropriate for sample sizes smaller than 50 [55]. Homogeneity of variance was not tested due to the single group design. A paired samples t test was conducted to assess mean differences between pretest and posttest scores. The null hypothesis posited no significant difference between the means, while the alternative hypothesis posited a significant difference. Statistical significance was determined at an alpha level of 0.05. To quantify the magnitude of learning gains, the normalized gain or N Gain was calculated [56]. This was done by subtracting the pretest score from the posttest score and dividing the result by the difference between the maximum score and the pretest score. An N Gain less than 0.30 indicates a low effect, a value between 0.30 and 0.70 indicates a moderate effect, and a value ≥ 0.70 indicates a high effect. Additionally, Cohen's d was calculated as a standardized effect size measure [57] by dividing the difference between the posttest and pretest means by the pooled standard deviation. The interpretation for Cohen's d defines 0.20 as a small effect, 0.50 as a medium effect, 0.80 as a large effect, and values ≥ 1.20 as a very large effect.

3. RESULTS AND DISCUSSION

3.1. Validity of the Digital Fun Thinkers Tool

3.1.1. Media Expert Validation

Four media experts evaluated the Digital Fun Thinkers tool across four dimensions, and the detailed results are presented in Table 2. All dimensions achieved Aiken's V values exceeding the 0.80 threshold. Ease of Use received the highest rating with a V value of 0.9896, which indicates exceptional usability. Qualitative feedback from media experts highlighted the intuitive navigation of the tool, the culturally appropriate integration of sign language, and the engaging gamified elements.

Table 2. Media Expert Validation Results (Aiken's V)

Dimension	Number of Items	Aiken's V	Interpretation
Display/Appearance	7	0.9514	High Validity
Language Use	5	0.9236	High Validity
Ease of Use	6	0.9896	High Validity
Usefulness/Utility	6	0.9688	High Validity
Overall Media Quality	24	0.9583	High Validity

3.1.2. Material Expert Validation

Four subject matter experts assessed the pedagogical quality and content accuracy of the tool, and the results are summarized in Table 3. All dimensions demonstrated high validity with V values of 0.80 or higher. The Adaptive dimension received the highest rating with a V value of 0.9792. Experts commended the alignment of the tool with curriculum standards, the developmentally appropriate content scaffolding, and the effective accommodation of the needs of DHH learners.

Table 3. Material Expert Validation Results (Aiken's V)

Dimension	Number of Items	Aiken's V	Interpretation
Self-Instructional	6	0.9250	High Validity
Self-Contained	5	0.9375	High Validity
Language	5	0.9167	High Validity
Adaptive	5	0.9792	High Validity
User-Friendly	5	0.9167	High Validity
Overall Material Quality	26	0.9350	High Validity

3.2. Practicality of the Digital Fun Thinkers Tool

Student practicality assessments revealed that the tool was highly usable and engaging. Descriptive statistics and individual student ratings are presented in Table 4. All students rated the tool in the Practical or Very Practical range, with an overall mean of 81.39 percent. Specifically, 8 students or 44.4 percent fell into the Very Practical category, while 10 students or 55.6 percent were in the Practical category. No students rated the tool as Less Practical or Not Practical. Qualitative observations noted high engagement, minimal frustration, and voluntary extended use during break times.

Table 4. Student Practicality Assessment Results (N = 18)

Statistic	Value
Mean Score (out of 60)	48.83
Mean Percentage	81.39%
Standard Deviation	2.67
Minimum Score	45 (75.00%)
Maximum Score	55 (91.67%)
Overall Category	Very Practical

3.3. Learning Responsibility Outcomes

Learning responsibility scores measured post intervention demonstrated that the Digital Fun Thinkers tool fostered high levels of learning responsibility among DHH students. The results are summarized in Table 5. The mean responsibility score of 66.28 exceeded the Very High threshold of 65. This indicates that the tool effectively promoted task completion, persistence, self-regulation, help-seeking, and goal orientation. Half of the participants achieved Very High levels while the other half achieved High levels, with no students exhibiting low or moderate responsibility.

Table 5. Learning Responsibility Assessment Results (N = 18)

Statistic	Value
Mean Score (out of 80)	66.28
Standard Deviation	3.12
Minimum Score	62
Maximum Score	73
Overall Category	Very High

3.4. Effectiveness of the Digital Fun Thinkers Tool on Conceptual Understanding

3.4.1. Descriptive Statistics and Assumption Testing

Pretest and posttest descriptive statistics are presented in Table 6. The mean pretest score of 42.22 indicated low baseline understanding. Following the intervention, the mean posttest score increased substantially to 80.28, representing a gain of 38.06 percentage points. Normality tests using the Shapiro Wilk method showed that both pretest and posttest distributions met the normality assumption with p values of 0.364 and 0.155 respectively. This justified the use of a parametric paired samples t test.

Table 6. Descriptive Statistics for Conceptual Understanding Scores (N = 18)

Measure	Pretest	Posttest	Gain
Mean	42.22	80.28	38.06
Standard Deviation	5.14	4.92	4.25
Minimum	32	72	28
Maximum	52	88	48
% of Maximum Score	42.22%	80.28%	+38.06%

3.4.2 Hypothesis Testing and Effect Size

The results of the paired samples t test in Table 7 reveal a statistically significant difference between pretest and posttest scores with a t value of 37.997 and a p value less than 0.001. The null hypothesis was rejected, confirming that the Digital Fun Thinkers tool significantly improved the conceptual understanding of science content among students. The magnitude of this improvement was further confirmed by an N Gain of 0.7338, which falls in the High Effect range. Additionally, the Cohen's d value of 7.57 represents an exceptionally large effect size, reflecting substantial learning gains and low within group variability.

Table 7. Paired-Samples t-Test Results

Variable	Mean Difference	SD	SE	95% CI	t	df	p (two-tailed)
Pretest - Posttest	38.06	4.25	1.00	[35.94, 40.17]	37.997	17	< 0.001

The findings of this study confirm that the Digital Fun Thinkers tool is a valid, practical, and effective solution for DHH education. The tool demonstrated high content validity with overall media and material scores of 0.9583 and 0.9350 respectively. Students perceived the tool as highly practical with an 81.39 percent satisfaction rate. Furthermore, the intervention led to very high levels of learning responsibility and produced statistically significant improvements in science conceptualization with a high N Gain of 0.7338 and a very large Cohen's d effect size of 7.57.

3.5. Interpretation of Findings in Relation to Research Questions

The present study provides converging evidence that the Digital Fun Thinkers tool is a valid, practical, and effective technology enhanced intervention for Deaf and Hard of Hearing students in an inclusive elementary school setting. The expert validation results show that both media and material aspects of the tool meet high standards of content validity and pedagogical appropriateness, as reflected in Aiken's V values above 0.80 across all dimensions [52]. Particularly high scores for Ease of Use (V = 0.9896) and Adaptive characteristics (V = 0.9792) indicate that experts perceived the tool as highly intuitive, accessible, and responsive to learner variability. These findings are congruent with Universal Design for Learning principles, which emphasize flexible, multimodal, and accessible instructional design [6], [58], [59]. The deliberate integration of Kata Kolok, an indigenous village sign language, further distinguishes this tool from many existing assistive technologies that are typically built around mainstream sign languages such as American Sign Language and British Sign Language [36], [60]. In this sense, the tool operationalizes UDL in a culturally responsive way that acknowledges the linguistic and cultural assets of the Bengkala community [61] rather than framing deafness solely as a deficit [62].

The expert ratings are reinforced by student practicality assessments. All 18 students rated the tool within the Practical or Very Practical categories, with a mean practicality score of 81.39 percent, which falls in the Very Practical range. This convergence between expert and user perspectives suggests that the tool is not only theoretically and technically sound but also workable in everyday practice from the standpoint of the learners themselves. Such alignment is consistent with research that highlights the importance of user centered and participatory design in educational technologies for marginalized populations, including DHH learners [63]. The involvement of local Kata Kolok signers and special education practitioners in the design and development stages appears to have contributed to the authenticity, clarity, and cultural appropriateness of the content, which are recognized as key factors in inclusive and culturally responsive pedagogy [64].

With regard to scientific conceptualization, the tool demonstrated very strong effects. Students' mean scores improved from 42.22 on the pretest to 80.28 on the posttest, with a mean gain of 38.06 points and a highly significant paired samples t value of 37.997 ($p < 0.001$). The normalized gain of 0.7338 indicates a high level of learning effectiveness [65], and the Cohen's d value of 7.57 represents an exceptionally large effect size when compared with conventional benchmarks of 0.50 for medium and 0.80 for large effects [66]. While effect sizes of this magnitude are rare in educational research, they become more interpretable when contextual factors are considered.

First, the low baseline performance observed in the pretest reflects long standing inequities in access to accessible and high quality science instruction for DHH students [67]. Such a floor effect provides a wide margin for improvement once appropriate instructional supports are introduced. Second, the intervention was carefully tailored to the cognitive and linguistic profiles of the target learners. The tool combined visual, interactive, and sign language based representations, which align with evidence that DHH learners benefit from visually salient, multisensory, and sign supported instruction [68]. Third, the close alignment between learning objectives, instructional activities, and assessment tasks likely strengthened construct validity and reduced measurement error [69]. Finally, observational data and student reports indicated sustained engagement throughout the intervention, supported by gamified elements such as progress tracking, badges, and tiered challenges [70]. These features are in line with research showing that gamification can enhance both cognitive and motivational outcomes in special education contexts [71].

Theoretically, the strong learning gains support constructivist models of learning, which posit that knowledge is actively constructed through interaction with meaningful tasks and scaffolds [72], [73]. Digital Fun Thinkers implemented constructivist principles by allowing students to manipulate representations, test their understanding through immediate feedback, and connect abstract ideas about living things to concrete and visual scenarios. This is particularly important for DHH students, who are often exposed to fragmented and text heavy instruction that does not adequately support conceptual development [19]. The tool also reflects principles from Mayer's Cognitive Theory of Multimedia Learning, including the reduction of extraneous information, the use of signaling, and the close temporal contiguity of visual and verbal information [74]-[76]. Empirical work on DHH learners indicates that careful application of these principles, especially visual signaling and minimized redundancy, is even more critical for this population than for hearing peers [68].

The study also demonstrates that the tool has meaningful effects on learning responsibility as an affective behavioral outcome. Post intervention scores placed all students in the High or Very High categories, with a mean score of 66.28 exceeding the Very High threshold. This pattern suggests that the intervention not only improved academic performance but also promoted more responsible and self directed learning behaviors, including task completion, persistence, help seeking, self regulation, and goal orientation [77]. Interpreted through Self Determination Theory, this result suggests that the learning environment fostered autonomy through self paced exploration, competence through clear and adaptive feedback, and relatedness through culturally familiar sign language content [78]. These three psychological needs are central to the development of intrinsic motivation and self regulated learning, which are especially important for DHH students who frequently experience repeated academic failure and low expectations in mainstream settings [79].

Existing research on self regulation and responsibility among DHH learners often reports moderate or low levels of learning responsibility, particularly in under resourced contexts where instructional support is limited [80]. The consistently high scores observed in this study therefore represent an encouraging departure from previous findings. They suggest that when digital learning environments are explicitly designed to support goal setting, progress monitoring, and intrinsic reward structures, they may function as empowerment technologies rather than merely compensatory tools. This insight aligns with broader work on gamification and motivation that documents positive effects of badges, progress indicators, and challenge structures on student engagement and self regulation [81], [82].

More broadly, the results resonate with and extend several strands of empirical and theoretical literature. Meta analytic reviews indicate that constructivist, inquiry based digital environments yield moderate to large effects on achievement [83], and that multimodal tools can be particularly effective for students with special educational needs [84], [85]. The current study adds to this evidence base by demonstrating large effects in a context that has received very little attention in prior research, namely an indigenous signing community in a rural, resource constrained setting. It also reinforces arguments from culturally responsive and inclusive education that insist on the value of local languages and cultural practices in designing equitable learning environments [86]. The use of Kata Kolok as a central medium of instruction exemplifies a shift from deficit based models to asset based approaches that view deaf communities as rich linguistic and cultural minorities rather than solely as groups with impairments.

At the same time, several limitations temper the interpretation of these positive findings. The one group pretest posttest design without a comparison group restricts the degree to which strong causal claims can be made [87]. Although the very short duration of the intervention, the use of equivalent but non identical test forms, and the magnitude of the effect sizes together reduce the plausibility of alternative explanations such as maturation or test familiarity, these threats cannot be ruled out entirely. The small sample size of 18 students also reflects the realities of working within a single, small DHH population, but it limits statistical power and precludes analyses of potential subgroup differences by gender, degree of hearing loss, or prior achievement.

External validity is another concern. The sociolinguistic and cultural context of Bengkala is highly distinctive, given the presence of a long standing village sign language and unusually high levels of social integration of deaf individuals [88]. It is therefore uncertain to what extent the findings can be generalized to urban DHH populations, to users of other sign languages, or to settings where deaf people face greater social marginalization. Replication studies in different geographic, linguistic, and cultural contexts will be essential to establish the broader applicability of the design principles used in Digital Fun Thinkers.

There are also limitations related to construct measurement. The science concept test, while psychometrically acceptable with adequate reliability and validity indices, focused on a single topic and primarily assessed factual, conceptual, and basic application level understanding [89]. Future work should investigate whether similar tools can support higher order learning outcomes such as critical thinking, problem solving, transfer, and long term retention. Learning responsibility was measured only once, after the intervention, which restricts the ability to infer change over time. Incorporating pre and follow up measures would provide a more robust basis for claims about causal effects on affective behavioral constructs.

Ecological validity also warrants attention. The intervention was implemented under relatively controlled conditions, with one student per tablet in a computer lab setting and limited competing classroom demands. In many real life classrooms, teachers must manage larger groups, varying levels of access to devices, and multiple curricular priorities. It remains an open question how well the tool would perform when embedded into regular classroom practice, for example in whole class instruction, small group work, homework, or blended learning arrangements.

These limitations point to several directions for future research. Multi site studies that include larger and more diverse DHH samples across different regions, sign languages, and school types would strengthen the evidence base and allow for more nuanced analyses of moderating factors [90]. Where ethically and logistically feasible, quasi experimental or randomized controlled trials could provide stronger causal evidence. Longitudinal studies with follow up assessments at 3 or 6 months would help clarify the durability of gains in both conceptual understanding and learning responsibility. Comparative studies could examine how Digital Fun Thinkers performs relative to other pedagogical approaches, such as traditional teacher led instruction, alternative digital tools, or hybrid models.

In addition, mechanism focused research is needed to understand how and why the tool works. Mixed methods designs combining learning analytics (for example, clickstream data, time on task, and error patterns), classroom observations, and qualitative interviews or think aloud protocols could reveal which design features are most influential for learning and motivation [91]. Implementation and scale up studies grounded in implementation science frameworks would help identify system level barriers and facilitators to broader adoption, including issues of infrastructure, teacher professional development, and policy alignment [92]. Finally, adapting and testing the underlying design principles of Digital Fun Thinkers for other learner groups, such as students with intellectual disabilities, autism spectrum disorder, or visual impairments, could extend the contribution of this work to a wider special education community [93].

Theoretically, this study makes at least three contributions. First, it extends constructivist theory into the under researched domain of indigenous DHH education by showing that constructivist principles can be effectively operationalized through culturally responsive, multimodal digital tools [94]. Second, by examining both conceptual understanding and learning responsibility, it advances a more holistic view of educational effectiveness that attends to the interdependence of cognitive, affective, and behavioral dimensions [95]. Third, the central role of Kata Kolok integrated digital media can be interpreted through a cultural historical activity theory lens, in which culturally mediated tools are seen as central to cognitive development [96]. The findings thus provide empirical support for the proposition that culturally and linguistically grounded artifacts can scaffold learning in powerful ways, particularly for learners who have historically been marginalized within mainstream educational systems.

4. CONCLUSION

This study demonstrates that the Digital Fun Thinkers tool is an effective, culturally responsive, and technology-enhanced learning intervention for Deaf and Hard of Hearing (DHH) elementary students in Bengkala Village, Indonesia. Developed through the ADDIE model and validated through expert review and empirical testing, the tool showed strong content validity, high practicality, and substantial effectiveness in improving students' scientific conceptual understanding, learning responsibility, and engagement. Significant gains in learning outcomes, supported by large effect sizes, highlight the potential of culturally grounded and gamified digital tools to address long-standing educational barriers faced by DHH learners. Beyond cognitive improvement, the intervention fostered positive learning behaviors, including persistence, self-regulation, and motivation, which are essential for long-term academic success. These findings contribute theoretically by extending constructivist and Universal Design for Learning frameworks into indigenous deaf education contexts, and practically by offering a scalable model for inclusive and accessible science education. However, the study is limited by its small sample size, single-site design, and short intervention duration. Future research should involve larger and more diverse populations, employ longitudinal and experimental designs, and explore broader learning outcomes across different subject areas. Further investigation into scalability, teacher readiness, and contextual adaptation is also recommended to support sustainable implementation. Overall, this study highlights the transformative potential of culturally responsive digital learning tools in promoting educational equity and meaningful learning experiences for marginalized learners.

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USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the preparation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried **out** entirely by the authors without the assistance of AI-based technologies.

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