Exploring Digital Storytelling for Enhancing Computer Science Education: A Case Study with Deaf Students

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***Abstract*—Deaf and Hard-of-Hearing (DHH) students face persistent barriers in computer science education due to the limited accessibility of traditional instructional methods. This study investigates the effectiveness of a Digital Storytelling (DS) approach, delivered via a custom-designed platform developed specifically for this research, in enhancing computational thinking and digital literacy among DHH middle school students in Kazakhstan. An experimental pre-test/post-test design, embedded within a real-world case study, was employed to enable a controlled comparison. Participants (n = 64) were assigned to either an experimental group, which received DS-based instruction, or a control group, which followed conventional textbook-based instruction. The StoryHub platform, integrating Kazakh Sign Language (KSL), subtitles, interactive animations, and reflection tools, was iteratively tested and refined in collaboration with teachers and DHH students to ensure accessibility, engagement, and alignment with national curriculum standards.**

Quantitative results demonstrated that the experimental group achieved significantly higher gains in computational thinking skills and digital literacy ($p < 0.001$) compared to the control group ($p < 0.05$), with a large effect size. Surveys and classroom observations further indicated increased motivation, active engagement, and learning autonomy among students using the DS platform. These findings highlight the transformative potential of culturally and linguistically accessible digital storytelling tools in supporting inclusive STEM education. The study offers implications for the design of future educational technologies for DHH learners and suggests that DS-based instruction can serve as a scalable, effective model for inclusive computer science education.

***Keywords*—deaf education, digital storytelling, inclusive and special education, accessible tools, deaf and hard of hearing**

I. Introduction

Deaf and Hard-of-Hearing (DHH) students continue to face persistent challenges in accessing quality education, particularly in technical fields like computer science [1]. Traditional instructional methods are often auditory or heavily text-based, creating significant barriers for students with hearing impairments [2]. This limitation is especially critical in STEM education [3], where abstract concepts require clear, accessible, and often multimodal explanations. In Kazakhstan, the situation is compounded by a lack of specialized resources and limited integration of sign language into educational content [4]. Existing teaching approaches fail to address the visual learning strengths and linguistic diversity of DHH students, leading to lower academic outcomes and reduced motivation in computing-related disciplines.

Several studies have pointed out that even widely used educational applications fail to meet accessibility standards for students with intellectual or sensory disabilities [5], further justifying the need for more inclusive, purpose-built learning environments such as the digital storytelling model proposed in this study.

This study explores the use of digital storytelling as a pedagogical approach to improve computational thinking and digital literacy among DHH students. Digital storytelling integrates animated visuals, local sign language, and interactive learning elements into a narrative-driven instructional format tailored to students' needs.

The primary research question is: Can a digital storytelling approach improve computational thinking and digital literacy more effectively than traditional teaching methods for deaf and hard-of-hearing students?

To address this, an experimental design was employed involving 64 students from inclusive and special classrooms in Kazakhstan. This study contributes to inclusive education by offering evidence-based insights into how storytelling technology can be used to overcome learning barriers in computer science education for DHH learners.

II. Literature Review

A. Challenges in Deaf and Hard-of-Hearing Education

DHH students often face persistent educational disparities compared to their hearing peers, particularly in abstract and language-intensive subjects [6–10]. Studies in the United States have consistently demonstrated performance gaps in reading, writing, and especially mathematics and problem-solving tasks, where DHH students underperform by several grade levels [11–13]. These challenges are not inherently cognitive but often stem from delays in language acquisition, especially for children born to hearing parents with no exposure to sign language during early development [11, 12]. In Kazakhstan, these issues are intensified by a lack of adapted teaching resources, inadequate teacher training, and minimal integration of Kazakh Sign Language (KSL) in instructional settings [14]. Reports have shown that many deaf students graduate from special or inclusive schools with significant deficiencies in core academic areas [3, 15].

In a recent exploratory study, Anwar *et al.* [16] investigated the effectiveness of STEM-based workshops designed specifically for deaf students, utilizing the Creative

Problem Solving framework to structure five-day sessions around environmental education. Their results showed notable gains in students' scientific literacy, communication, and collaborative problem-solving skills. Although their method involved in-person workshops, the results highlight the importance of organized, relevant, and varied learning experiences for deaf and hard of hearing students—ideas that closely relate to this study's use of interactive digital storytelling.

B. Digital Storytelling in Education

Digital Storytelling (DS) is a pedagogical method that integrates narrative structures with multimedia tools—such as animation, visuals, and voice-over—to create engaging, personalized learning experiences [17, 18]. It has been widely used in language arts, social studies, and emotional development education [18]. DS supports constructivist and experiential learning principles by enabling students to connect personal and academic content through story. In mainstream contexts, studies show that DS improves student motivation, engagement [18, 19], and critical thinking [19], particularly among younger learners. It also aligns well with Universal Design for Learning (UDL) principles by incorporating multiple means of representation, engagement, and expression [20].

C. Application of Digital Storytelling for Deaf Students

A limited but growing body of research has examined the application of digital storytelling for DHH students. This research draws attention to the promise of digital storytelling as a tool to enhance language skills, cultural expression, and personal identity among Deaf and Hard of Hearing (DHH) students. By allowing these students to create and share their narratives, digital storytelling promotes a sense of community and belonging, which is essential for their academic and social development. Flórez-Aristizábal *et al.* [21] demonstrated how digital storytelling supported deaf children's literacy development by combining visual language with narrative thinking. Educators in this study found that the approach offered flexible, engaging alternatives to traditional text-bound materials, which often fail to accommodate the linguistic diversity within deaf populations. Another project [22] investigated an e-learning tool designed for deaf Arab children, which utilized digital storytelling to enhance language development; however, it was still in the prototype stage. These studies support the idea that DS holds promise for inclusive education but have largely focused on early literacy skills rather than STEM or computational subjects. Rakhimzhanova *et al.* [23] applied AR-based mobile learning to improve digital literacy for primary students with special educational needs in Kazakhstan. Their quasi-experimental design demonstrated a statistically significant improvement in learning outcomes, especially among students with hearing and motor disabilities. While their research focused on younger learners in primary school, the current study extends this exploration to middle school students and shifts the emphasis toward computational thinking and interactive storytelling as core design principles.

D. Gaps in Applying DS in Computer Science Education

Despite the proven success of DS in language and arts education, its application in STEM, particularly in computer science for DHH learners, remains underexplored. Few studies have investigated how digital storytelling can support the understanding of abstract computational concepts, algorithms, or networks [24–27]. In Kazakhstan, the absence of interactive, sign-language-accessible digital tools inclusive approaches. While some inclusive pedagogies have introduced multimedia components, they often lack sign language integration and do not adhere to systematic instructional design principles tailored to diverse learner needs. Adler [28] highlights the critical language and communication barriers that DHH individuals face in Science, Technology, Engineering, Mathematics, and Medicine (STEMM) careers, as well as the need for multimodal, accessible instruction to address both linguistic diversity and real-world inclusion challenges. Thus, a clear gap exists in applying DS to computer science education for deaf students, which this study aims to address.

A meta-analysis of technology-enhanced learning for students with disabilities confirmed that most educational tools remain heavily text-based, limiting accessibility for DHH students who benefit from richly visual and interactive environments [29]. Existing DS implementations in inclusive education tend to rely on static narratives or fixed pathways, offering limited interactivity and personalization. In contrast, interactive DS models featuring branching storylines, adjustable pacing, and multimodal engagement have shown increased effectiveness, particularly among neurodiverse and linguistically diverse populations [25–30]. However, such models are rarely examined within the context of DHH learners in computer science education. Growing attention to inclusive education technologies has not yet translated into scalable practice. A recent five-year review by Buzzi *et al.* [31] highlights that STEM education continues to lack widely accessible and empirically validated tools for students with disabilities. The review stresses the importance of implementing real-world, personalized, and multimodal solutions especially for learners with sensory impairments such as DHH students.

There also remains a lack of localized research and culturally relevant tools that incorporate local sign languages. This study addresses that gap by developing and evaluating a digital storytelling platform aligned with the national curriculum and adapted to Kazakh Sign Language, offering a replicable framework for inclusive computer science education.

III. MATERIALS AND METHODS

A. Research Design

This research employed a case study approach at an inclusive school in Kazakhstan, utilizing an experimental design with pre- and post-tests to examine the impact of digital storytelling on students' computational thinking skills. A total of 64 students from an inclusive school in Kazakhstan participated. Students were assigned to either the experimental group or the control group using a balanced assignment strategy, ensuring comparable distributions in terms of age, sign language proficiency, and baseline academic performance. The experimental group engaged in narrative-driven lessons, sign language-integrated instructional videos, and interactive DS-based activities, while the control group received traditional instruction. Pre- and post-tests were used to assess students' computational thinking and digital literacy. These were supplemented by short surveys after each session, which provided additional insights into student understanding and engagement. This combined methodological approach allowed for a comprehensive evaluation of both cognitive and affective learning outcomes associated with the DS intervention.

The intervention lasted eight weeks, with one 45-minute session conducted each week. The study phases are described in Table 1. Both groups followed the same curriculum to ensure consistency in content delivery, with the only difference being the mode of instruction and materials used.

Table 1. The study phases

Phase	Duration	Activities
Pre-Test	Week 1 1 session	Assessment of computational thinking and digital literacy through tests. The assessment of participants' sign language proficiency.
Instructional Sessions	Weeks 2–7 6 sessions	Experimental group: Engaged with digital interactive storytelling materials. Control group: Received traditional instruction using text-based resources.
Post-Test	Week 8 1 session	Evaluation of learning outcomes and post-test results. Evaluation of changes in student engagement and understanding through surveys and classroom observation.

B. Participants

The study involved 64 DHH students aged 11 to 16, recruited from special and inclusive classes at a public school in Astana, Kazakhstan. The participants' characteristics are presented in Table 2. Participants were selected based on the following inclusion criteria: (1) enrollment in grades 5–9; (2) formal diagnosis of hearing impairment; and (3) parental or guardian consent to participate. Students with profound intellectual disabilities that prevented participation in digital tasks were excluded. Group assignment was balanced based on age and baseline performance to ensure comparability between experimental and control groups. All participants had hearing impairments of varying degrees, accompanied by diverse speech and language challenges. Developmental delays (cognitive and/or motor) and delayed speech and language development were common among the participants, affecting 51.5% and 76.5% of the sample, respectively. Additionally, 23.4% experienced reading and writing difficulties. These varied needs highlighted the necessity for an adaptable, visually rich, and interactive instructional approach specifically designed to support communication, comprehension, and engagement for DHH learners.

Table 2. Participants' characteristics

	Characteristics	Frequency	Percentage
Gender	Female	30	46.8%
	Male	34	53.2%
Age Group	11–12 years	21	33%
	13–14 years	23	36%
	15–16 years	20	31%
Accompanying Diagnoses	Hearing impairment	64	100%
	Developmental delays (cognitive and motor)	33	51.5%
	Delayed speech and language development	49	76.5%
	Absence of speech due to hearing impairment	10	15.6%
	Reading and writing difficulties	15	23.4%

C. Instructional Design

Experimental Group (Digital Storytelling Approach): Text-based textbook content was transformed into animated short videos with subtitles, sign language translations, and interactive elements (e.g., embedded quizzes and feedback forms). The lessons emphasized multimodal learning, incorporating visuals, narration, and interactivity to support engagement and comprehension.

Control Group (Traditional Approach): Received standard instruction using lecture-based methods and text-based materials without animations or interactivity.

D. Content Adaptation

The educational content, originally derived from the national school curriculum, was transformed into DS format (see Fig. 1) to better accommodate the learning needs of students with hearing impairments. Unlike traditional textbook-based presentations, the adapted material was delivered as animated videos enriched with subtitles, visual elements, and sign language interpretation. This multimodal approach was designed to enhance accessibility and comprehension by combining text with dynamic visual representations.

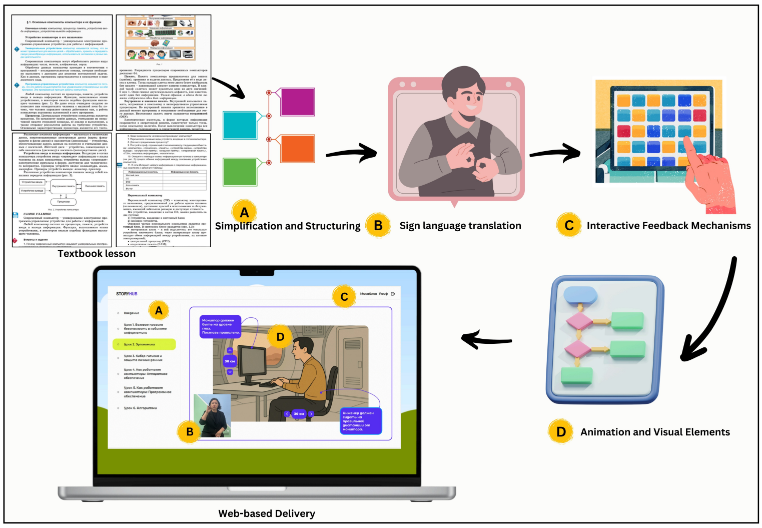

Fig. 1. Content adaptation and digital delivery workflow for StoryHub platform.

To ensure that the integrity of the national Information Communication Technologies (ICT) curriculum was preserved, all content simplification and translation procedures were guided by instructional design principles and verified by subject-matter experts. The adaptation process did not involve cognitive reduction but rather reformatted the content for visual and linguistic accessibility. Long textual explanations were segmented and restructured without omitting core learning objectives. Sign language translation was performed in collaboration with certified KSL interpreters and reviewed by ICT teachers to maintain conceptual accuracy and age-appropriate terminology. This translanguaging process—bridging written, signed, and visual forms—was essential to support meaning-making, not simplification. Quality control was conducted through iterative feedback sessions with teachers and student piloting, which informed refinements to both language and visual representations.

Fig. 2 presents a visual overview of the content adaptation process. The steps are described in detail below.

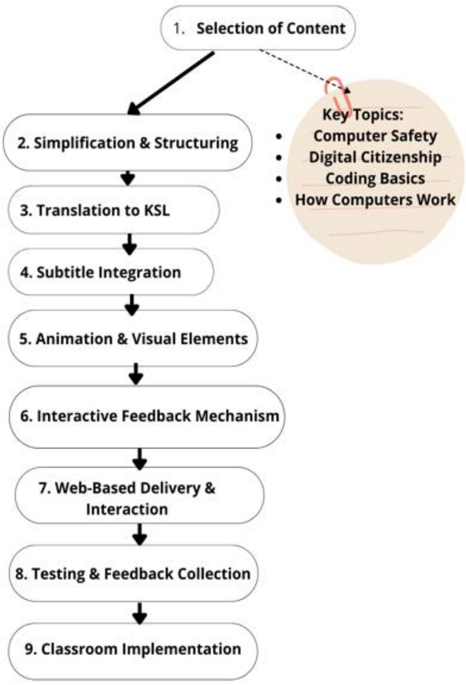

Fig. 2. Flowchart of the content adaptation process.

1) Selection of content

Key topics were selected from the ICT subject's long- and short-term curriculum plans, based on their relevance to learning objectives and the needs of DHH students. The four selected topics included:

- Basic Computer Safety (safe usage, ergonomics, cyber hygiene),
- Internet Safety and Digital Citizenship (cyberbullying prevention, responsible online behavior),
- Coding Basics (block-based programming),
- How Computers Work (hardware, software, and networks).

2) Simplification and structuring

Long and complex textbook paragraphs were rewritten into shorter, clearer segments using simple, accessible language. Key terms and definitions were visually distinguished to improve focus and understanding.

3) Translation to Kazakh sign language

A professional interpreter translated the simplified content into KSL. The sign language components were recorded as video inserts featuring a live interpreter to ensure linguistic and cultural accuracy.

4) Subtitle integration

Subtitles were added to all videos to support students with varying levels of sign language proficiency. The readability of subtitle text was verified using the Flesch Reading Ease Index, with all content meeting or exceeding a score of 60—indicating suitability for teenagers and general audiences.

5) Interactive feedback mechanisms

Each lesson included a dedicated section for students to submit reflections, questions, or comments. These responses helped reinforce learning and provided additional feedback for iterative improvement.

6) Animation and visual element development

Short, animated videos were developed to present key concepts visually, replacing traditional text-based explanations. The animations were designed following Multimodal Learning Theory [30], integrating visual, textual, and interactive elements to enhance comprehension. Additionally, Universal Design for Learning (UDL) principles were applied by incorporating sign language interpretation, subtitles, and interactive features to ensure accessibility for diverse learners [19]. To create the videos, Blender 3D was used for modeling and animation, and Adobe Premiere Pro was used for editing and adding subtitles. The chosen tools ensured high-quality visual content and adaptation for users with different needs, including support for sign language and text subtitles.

7) Web-based delivery and student interaction

During the intervention, students accessed the StoryHub platform individually using school-provided laptops or tablets. Lessons were delivered entirely online, with each session structured around an animated narrative combined with interactive tasks. Students navigated the lessons autonomously, engaging with embedded quizzes, animations, and reflective note-taking opportunities.

The platform's design emphasized multimodal accessibility, offering synchronized sign language videos, visual storytelling, and simplified written captions to cater to diverse communication needs. Observational data indicated that students maintained sustained visual attention during animations, actively participated in interactive segments, and demonstrated autonomy in progressing through lesson tasks without frequent instructor prompting. Engagement logs collected from the platform, including quiz completion rates and reflection entries, provided additional insights into behavioral patterns and learning persistence.

The narrative-driven design, paired with interactive challenges aligned with core computer science concepts, fostered both cognitive engagement and emotional investment, positioning students as active participants in a collaborative virtual mission environment.

8) Testing and feedback collection

Prior to full implementation, the digital storytelling content underwent a pilot phase with a representative group of DHH students. This phase focused on evaluating the usability and pedagogical effectiveness of the platform. Structured observations and informal interviews with students and teachers provided actionable feedback on areas such as animation pacing, visual clarity, and the accuracy of Kazakh Sign Language integration. Insights gathered during this stage informed iterative refinements to the instructional materials and interaction design. Enhancements were made to improve visual engagement, optimize sign language synchronization, and ensure that interactive components supported rather than hindered comprehension. This continuous feedback loop played a critical role in aligning the platform with the diverse communication needs and learning preferences of the target population.

9) Classroom implementation

The final version of the DS-based lessons was integrated into regular computer science classes. Teachers facilitated the use of digital materials, guided discussions, and conducted follow-up activities to reinforce learning outcomes.

E. Platform Development

To facilitate the digital storytelling experience, a web-based application titled **StoryHub** was developed and deployed using the **Bubble.io** platform. Prior to the intervention, all participants registered in the application to enable tracking of individual progress, quiz responses, and test results. This data was securely stored in Bubble's integrated backend database and later used by both researchers and instructors to evaluate learning outcomes and engagement levels.

Bubble.io was selected due to its robust no-code development environment, which allowed for rapid prototyping, seamless integration of multimedia content, and efficient adaptation of lesson modules. Its built-in support for custom workflows, user authentication, and real-time data logging provided a stable and scalable infrastructure for delivering interactive learning experiences. Moreover, Bubble's visual editor enabled iterative updates to instructional content based on classroom feedback, allowing the platform to evolve during the pilot phase without requiring major redevelopment.

The instructional design of StoryHub was organized into narrative-based modules tailored for 5th- and 6th-grade DHH students. The storyline unfolds in a futuristic space setting, where learners are recruited to assist a malfunctioning robot named Altin in recovering lost data from a Martian base. Each lesson is framed as a mission—starting with foundational topics such as **digital safety and ergonomics,** then progressing to **hardware vs. software, cyber hygiene,** and **algorithms** including **binary, decimal, and hexadecimal number systems.**

Throughout the storyline, students interact with animated characters, explore hazards in the virtual environment, solve logic-based puzzles, and complete embedded quizzes. These elements are tightly aligned with national ICT curriculum standards and supported by **Kazakh Sign Language interpretation, visual narratives,** and **interactive feedback tools.** Each lesson page includes an animated explanation segment, sign language overlays, and an optional note-taking feature to encourage self-reflection and reinforce comprehension. Fig. 3 illustrates a sample interface from StoryHub, showing how the visual storytelling format immerses students in meaningful, context-rich learning tasks.

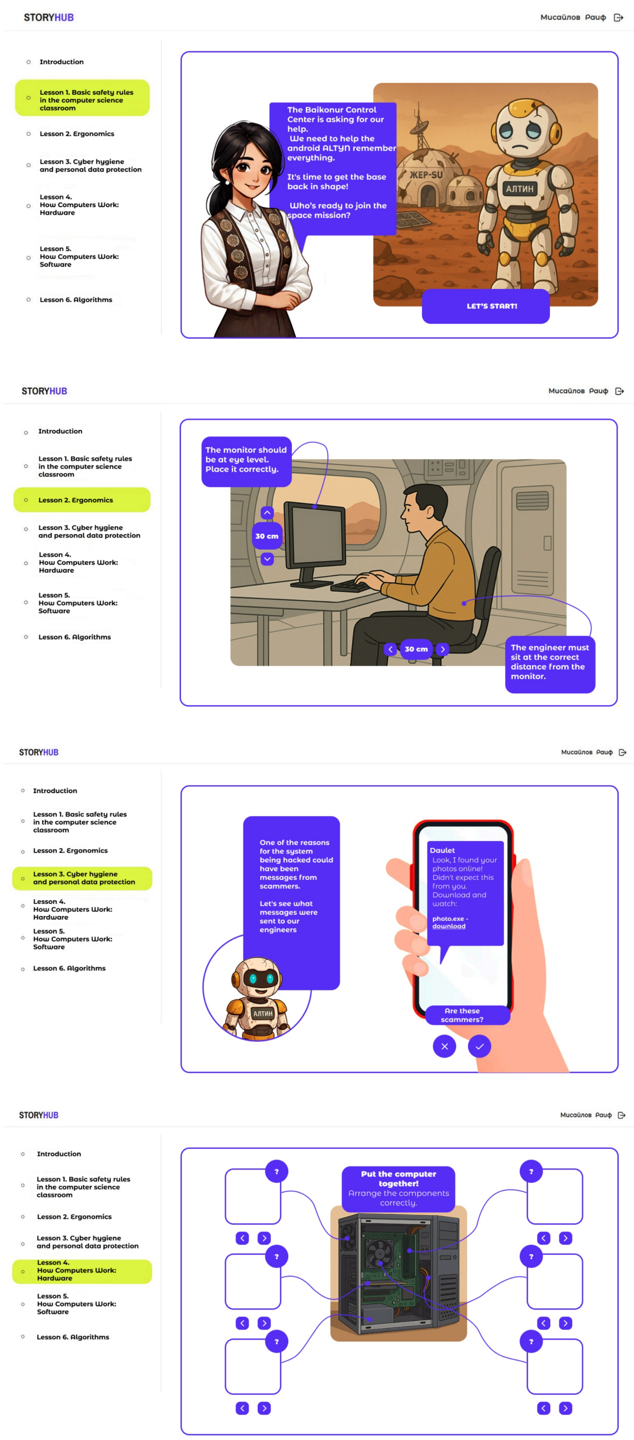

Fig. 3. Sample interfaces from StoryHub.

F. Sign Language

Students primarily communicated using Kazakh Sign Language (KSL), while some relied on written text for instructions and explanations. This diversity in communication modalities necessitated the adaptation of DS content through the integration of local sign language translations, subtitles, and visual supports to ensure accessibility and comprehension for all learners.

It has been proposed that recognizing the group rights of deaf individuals promotes greater inclusion by ensuring cultural and linguistic accessibility [32]. For instance, sign languages should be acknowledged and treated as fully valid languages, equivalent to spoken ones [33, 34].

In the current study, participants' proficiency in KSL was assessed by a qualified sign language teacher prior to the intervention, using a five-point scale (1 = very limited proficiency; 5 = native-like proficiency), and results are presented in Table 3. This assessment served two purposes: to determine the necessity of translating learning materials into sign language and to support the effective integration of new instructional content in KSL.

Table 3. Local sign language proficiency among participants

Proficiency rate	Freq.	%
1: Novice: No knowledge of sign language.	12	18.75
2: Basic: Limited knowledge with a few signs, unable to communicate.	9	14.07
3: Intermediate: Understands well, with a small vocabulary.	16	25
4: Advanced: Understand and use a moderate number of signs.	23	35.93
5: Fluent: High proficiency; understands and communicates freely in sign language.	4	6.25
Total number of students	64	100

The assessment results indicated that both KSL translation and written subtitles were essential to support comprehension across the full range of proficiency levels. Some students relied primarily on visual sign input, while others benefited more from reading subtitles. To further investigate this, survey responses were cross-referenced with participants' KSL proficiency scores to examine how fluency levels influenced engagement and understanding during digital storytelling sessions.

The sign language translation process was conducted in collaboration with a nationally certified Kazakh Sign Language (KSL) interpreter with over five years of experience in educational and technical translation. To ensure conceptual accuracy and alignment with computing terminology, the interpreter collaborated with two bilingual Deaf educators who possess formal training in STEM education. These Deaf consultants reviewed all technical vocabulary and validated the signs for consistency, clarity, and accessibility. Where standardized signs for computing terms did not exist, new representations were co-developed with input from the Deaf professionals, ensuring linguistic appropriateness and alignment with the intended learning outcomes. This collaborative approach ensured that sign representations were pedagogically accurate and culturally resonant.

G. Data Collection and Instruments

Data collection in this study employed a combination of quantitative and qualitative methods to provide a comprehensive evaluation of the intervention. All instruments were validated for reliability and appropriateness for the target population, ensuring the robustness and credibility of the findings.

The pre- and post-tests consisted of 10 items aligned with national middle school ICT standards, covering algorithmic thinking, coding basics, and problem-solving. Each test included a mix of multiple-choice and open-ended questions. Test items were developed in collaboration with ICT teachers experienced in DHH education and validated by a panel of five experts in computer science and inclusive pedagogy. A pilot test yielded a Cronbach's alpha of 0.87, indicating high internal consistency.

Surveys administered after each lesson included Likert-scale items and open-ended questions measuring comprehension, motivation, and engagement. Observational data were collected using a structured protocol based on thematic coding of classroom behaviours, including participation, peer interaction, and autonomy. Observers were trained teachers fluent in Kazakh Sign Language (KSL).

1) Pre- and post-tests

Pre- and post-tests were administered to assess students' computational thinking skills and understanding of computer science concepts before and after the intervention. Each test included 10 questions—comprising both multiple-choice and open-ended formats—aligned with the national middle school curriculum. The content focused on algorithmic thinking, basic programming concepts, and general problem-solving.

The tests were designed to capture changes in students' standardized performance and were developed by ICT teachers with experience in deaf education. The test items reflected key computational thinking dimensions such as problem-solving, decomposition, pattern recognition, abstraction, and algorithmic thinking, based on frameworks proposed by Wing [35] and Shute *et al.* [36]. To ensure content validity, a panel of experts in computer science education and inclusive pedagogy reviewed the assessment instruments. A pilot implementation during the platform validation phase yielded a Cronbach's alpha of 0.87 [37], indicating high internal consistency. The tests were administered under standardized classroom conditions, with instructions provided by teachers but no additional support, ensuring the integrity of the results.

2) Surveys

In addition to pre- and post-testing, structured surveys were administered to students in the experimental group following each instructional session to assess comprehension, motivation, and engagement. Each survey consisted of three sections: (1) content understanding, (2) motivation toward the topic, and (3) engagement with the digital storytelling (DS) platform. The comprehension section included five multiple-choice questions aligned with the core learning objectives of each lesson, designed to evaluate knowledge retention and conceptual grasp. The motivation section comprised five items using a Likert scale (1–5) and multiple-choice formats, capturing students' interest, willingness to continue studying the topic, and preferences for instructional format. The engagement section included five questions assessing students' perceived task difficulty, level of interactivity, enjoyment, and self-reported ability to explain the content to peers. Surveys were developed in simple, age-appropriate language suitable for Deaf and Hard-of-Hearing (DHH) middle school students and were piloted for clarity prior to implementation. Responses were collected through the StoryHub platform using participant identifiers, ensuring linkage with other data sources while maintaining confidentiality. Descriptive statistics were used to summarize the survey results, and trends in engagement and motivation were analyzed across sessions to triangulate findings from standardized tests and classroom observations. Sample questions from the survey are presented in Table 4.

Table 4. Sample survey questions

No.	Survey Item	Response Scale (1–5 Likert)
1	I found the lesson interesting.	1 (Strongly disagree) to 5 (Strongly agree)
2	I was actively engaged during the lesson.	1 (Strongly disagree) to 5 (Strongly agree)
3	I prefer learning through digital storytelling over traditional methods.	1 (Strongly disagree) to 5 (Strongly agree)
4	I interacted with the lesson materials (e.g., quizzes, animations).	1 (Strongly disagree) to 5 (Strongly agree)
5	I feel confident explaining the lesson content to a peer.	1 (Strongly disagree) to 5 (Strongly agree)

Post-lesson survey structure is presented in Table 5. Surveys were designed in simple, accessible language and supplemented by Kazakh Sign Language (KSL) interpretations.

Table 5. Post-lesson survey structure

Survey Section	Number of Questions	Question Typ	Purpose
Content Understanding	5 per lesson	Multiple-choice (correct/incorrect)	Assess students' grasp of computer science concepts taught in each lesson
Motivation	5 per lesson	Likert scale (1–5) and multiple-choice	Evaluate students' interest, willingness to continue learning, and format preference.
Engagement	5 per lesson	Likert scale (1–5) and reflective questions	Measure active participation, task difficulty perception, and self-confidence in explaining content.

3) *Observational Data*

Qualitative observational data were collected during instructional sessions to capture student behavior and engagement. Observers documented several indicators, including time spent on tasks, collaboration patterns, individual problem-solving strategies, and visible signs of motivation—such as sustained attention and persistence when facing challenges. Observation notes were analyzed thematically using qualitative analysis software to identify recurring patterns, such as heightened engagement during interactive activities or difficulties in navigating complex tasks.

IV. Results

A. *Pre- and Post-Test Results*

Pre- and post-tests were administered to evaluate changes in students' computational thinking and computer science knowledge following the intervention. The experimental group, which engaged with the digital storytelling (DS) platform, demonstrated a significant improvement in post-test scores (M = 76.4, SD = 7.82) compared to the control group (M = 62.9, SD = 8.64). Paired-sample t-tests indicated that the improvement within the experimental group was statistically significant ($t(31) = 8.96$, $p < 0.001$), while the control group also showed a smaller but significant gain ($t(31) = 2.58$, $p < 0.05$). Between-group comparisons using the Mann-Whitney U test confirmed that the experimental group significantly outperformed the control group on the post-test ($U = 290$, $p < 0.001$). These results, alongside large effect sizes observed, provide strong evidence for the effectiveness of the DS-based intervention in enhancing computational thinking and digital literacy among DHH students.

Descriptive statistics for both groups are presented in Table 6. The experimental group showed a notable improvement of 21.4 points, compared to a 7.5-point gain in the control group. Both gains were statistically significant, though the effect size in the experimental group was considerably larger, indicating a stronger impact of the digital storytelling intervention.

Table 6. Pre- and post-test scores, improvements, and effect sizes for experimental and control groups

Group	Pre-Test Mean	Post-Test Mean	Improvements	Effect Size
Experimental	55.0 (±9.6)	76.4 (±7.8)	+21.4	Large p-value < 0.001
Control	55.4 (±9.5)	62.9 (±8.6)	+7.5	Small p-value < 0.05

Fig. 4 visualizes the difference in pre- and post-test scores between the experimental and control groups. While both groups improved, the experimental group demonstrated a significantly greater gain, further supporting the impact of the digital storytelling intervention on student learning outcomes.

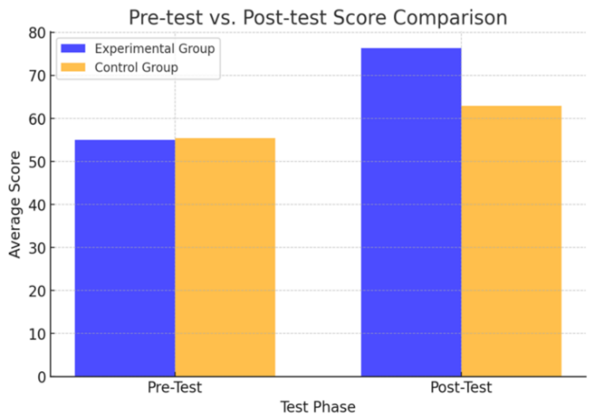

Fig. 4. Pre-test and post-test score comparison between experimental and control groups.

The normality of pre- and post-test score distributions was assessed using the Shapiro-Wilk test. Results indicated that the data deviated from a normal distribution ($p < 0.05$), supporting the use of non-parametric tests alongside traditional parametric methods. Consequently, Wilcoxon signed-rank tests and Mann-Whitney U tests were employed to validate group differences and within-group changes.

B. *Survey Results on Motivation and Engagement*

Survey responses collected after each session revealed new perspectives on students' motivation and engagement with the Digital Storytelling (DS) approach. Overall, students reported high levels of interest and enjoyment across all lessons, with 78% consistently rating their interest as "4" or "5" on the five-point Likert scale. A majority of students (over 80%) indicated a preference for continuing learning in the interactive digital format. Engagement metrics were similarly positive: approximately 85% of students reported actively interacting with the platform's quizzes and animations, and more than 70% stated that they could confidently explain the lesson content to a peer after completing the sessions. These findings align with the observed increases in post-test performance and suggest that the DS-based platform effectively supported both cognitive and affective aspects of learning.

As shown in Fig. 5, the majority of students reported high motivation, a strong preference for continuing in the digital storytelling format, active engagement with interactive elements, and confidence in explaining the lesson content to others.

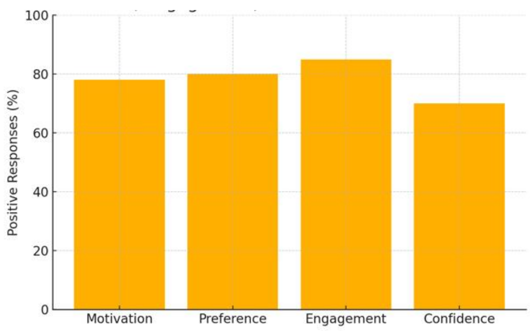

Fig. 5. Student motivation, engagement, and confidence levels post-intervention.

C. Observational Findings

Qualitative classroom observations provided further insights into student behaviors during DS sessions. Observers noted that students generally maintained higher attention spans during animated storytelling sequences and interactive problem-solving tasks compared to traditional lecture-based lessons. Increased instances of peer collaboration, persistence in overcoming challenges, and independent engagement with content were recorded. Thematic analysis of observation logs identified five recurring behavioral patterns: visual engagement, peer collaboration, autonomy, task persistence, and emotional response. These themes and their associated behavioral indicators are summarized in Table 7.

Table 7. Observational Themes and behavioural indicators recorded during digital storytelling sessions

Theme	Description	Observed Indicators
Visual Engagement	Student remains visually focused on animated or interactive content throughout the session.	Eye contact with screen; attention to KSL or animations.
Peer Collaboration	Student interacts with peers to solve problems or clarify concepts.	Asking questions, sharing screens, or signing to peers.
Autonomy	Student navigates the platform independently without repeated teacher prompting.	Uses note-taking and completes quizzes independently.
Task Persistence	Student continues working on a task despite difficulty, showing resilience.	Retries tasks; revisits animations or instructions.
Emotional Response	Student displays visible excitement, satisfaction, or frustration during activities.	Smiling, gesturing, or showing signs of focus/frustration.

Note: Observations were conducted by trained educators fluent in KSL, ensuring accurate interpretation of student behaviors.

D. Hypothesis Testing

To assess the impact of digital storytelling, we tested the following hypotheses:

H_0 (Null Hypothesis): The digital storytelling approach does not significantly improve computational thinking and digital literacy compared to traditional instruction.

H_1 (Alternative Hypothesis): The digital storytelling approach significantly improves computational thinking and digital literacy.

A paired t-test and Wilcoxon signed-rank test confirmed a significant improvement in the experimental group ($t(31) = 7.88$, $p < 0.001$; $W = 335$, $p < 0.001$), leading to the rejection of H_0.

Next, a Mann-Whitney U test was performed to compare post-test scores between the experimental and control groups.

Mann-Whitney U test results: $U = 290$, $p < 0.001$ (experimental group outperformed control)

This reinforces the conclusion that digital storytelling is significantly more effective than traditional instruction.

E. Correlation Analysis

A Pearson correlation analysis was conducted to explore relationships between student engagement (results from conducted survey) and learning outcomes.

Engagement vs. Post-Test Performance: $r = 0.54$, $p < 0.01$. Moderate positive correlation is presented in Fig. 6.

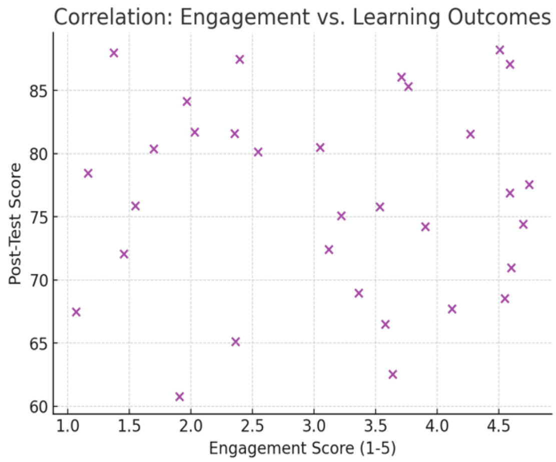

Fig. 6. Correlation: engagement vs. learning outcomes.

Sign Language Proficiency vs. Test Performance: $r = 0.48$, $p < 0.05$ (students with better sign language skills performed better)

These findings suggest that higher engagement and sign language proficiency are associated with better learning outcomes.

F. Summary of Findings

Statistical analyses using both parametric (paired-sample t-test) and non-parametric (Wilcoxon signed-rank test and Mann-Whitney U test) methods consistently confirmed the effectiveness of the Digital Storytelling (DS) intervention in improving learning outcomes among DHH students.

The experimental group demonstrated a large effect size (Cohen's $d = 1.2$) compared to a small effect size in the control group ($d = 0.4$), indicating that the DS-based approach had a substantial impact on computational thinking and digital literacy development.

Positive correlations were observed between student engagement, sign language proficiency, and post-test performance, reinforcing the importance of accessible, multimodal instructional strategies for DHH learners.

Collectively, these findings provide robust evidence that digital storytelling constitutes a highly effective pedagogical tool for enhancing computational thinking skills and digital literacy within inclusive educational settings.

V. Discussion

Recent research on DHH students [33] emphasizes the importance of integrating multimedia tools, such as sign language videos and interactive exercises, to enhance accessibility and engagement in STEM education. The findings of this study align with these insights, demonstrating that Digital Storytelling (DS) fosters deeper engagement and supports computational thinking development. By adapting educational content to Universal Design for Learning (UDL) guidelines, this study provides a scalable and adaptable approach that can be applied across diverse educational settings.

The results directly support the study's primary objectives. The experimental group exhibited a statistically significant improvement in computational thinking skills, as indicated by the post-test scores ($t(31) = 7.88$, $p < 0.001$). This confirms the hypothesis that interactive storytelling effectively scaffolds abstract computational concepts, making them more accessible to students who benefit from visual and narrative-based learning. Additionally, the Mann-Whitney U test ($U = 290$, $p < 0.001$) highlights that the experimental group significantly outperformed the control group, reinforcing the effectiveness of the DS approach.

A closer analysis of the Computational Thinking (CT) outcomes revealed that students in the experimental group demonstrated marked improvements in specific CT subskills, particularly in algorithmic thinking, abstraction, and decomposition. The narrative structure of the digital storytelling lessons helped students conceptualize algorithms as sequences of events with a beginning, middle, and end—making them more relatable and easier to retain. Visual cues and sign-supported explanations further reinforced abstraction by helping learners generalize patterns across examples. Interactive tasks such as drag-and-drop coding exercises and visual logic flows supported decomposition by prompting students to break problems into smaller, manageable parts. In contrast, students in the control group, who engaged primarily with text-based explanations and lecture-style instruction, showed more modest gains in these subdomains, likely due to reduced visual scaffolding and limited task interactivity. These findings suggest that the design of multimodal, narrative-driven learning environments may be especially effective for cultivating foundational CT skills among DHH learners.

Furthermore, survey and observational data revealed higher levels of engagement and greater perceived relevance of lessons among students using the DS approach. This aligns with findings in the Results section, where engagement scores correlated positively with learning outcomes ($r = 0.54$, $p < 0.01$). These results support the study's objective of enhancing motivation among DHH learners through innovative teaching methods. Notably, interaction logs indicated a gradual decline in reliance on scaffolding features, suggesting that students developed autonomy and confidence over time.

This study contributes to the field by addressing a significant research gap. While previous studies emphasize the need for technology integration in inclusive education [35], there is a lack of empirical research involving real-world classroom implementations with DHH students in special and inclusive schools. Unlike studies by Marschark *et al.* [36], which challenge the assumption that DHH students are predominantly visual learners, our findings provide empirical evidence that visually rich storytelling enhances computational thinking. This highlights the potential of tailored digital tools to bridge learning gaps in STEM education.

The findings also suggest that engaging narratives, visual interactivity, and structured scaffolding features contribute to increased intrinsic motivation, making learning both enjoyable and relevant. The observed decline in scaffolding use over time further emphasizes the role of DS in fostering self-directed learning. These insights align with the Results section, where the Wilcoxon Signed-Rank Test ($W = 335$, $p < 0.001$) confirmed a significant improvement in learning outcomes over time.

Digital storytelling has the potential to transform teaching practices by making abstract computational concepts more accessible and engaging, particularly for DHH students. However, for successful implementation, systemic support is required to integrate tailored digital tools into inclusive education frameworks. This study underscores the importance of designing adaptable tools that cater to diverse learning needs, with features such as multilingual sign language support and customizable pacing. Future research should explore long-term effects of DS-based learning, particularly in enhancing STEM-related career pathways for DHH students.

This study was conducted with 64 students from a single inclusive school in Astana, Kazakhstan, which may limit the generalizability of the findings to broader populations. To strengthen the applicability of the results, future research should include larger and more diverse samples across different educational settings.

The research primarily focused on immediate learning outcomes, such as computational thinking skills and engagement observed during the intervention. However, the long-term sustainability of these outcomes remains unexplored. Future studies should examine whether these gains persist over time and extend to other areas of academic performance.

Although efforts were made to standardize instructional delivery, variations in teacher facilitation across groups may have influenced the results. Investigating the impact of teacher-led delivery and providing additional training for facilitators could help mitigate this limitation in future implementations.

This study involved minor participants, requiring prior approval from the university's ethics committee and parental consent. Written informed consent was obtained from the parents of all participants before their involvement in the study. Additionally, class teachers were briefed on the study's objectives, methodology, and their role in supporting the research process.

To ensure participant confidentiality and data protection, all collected data were anonymized, and strict data security protocols were implemented. Consent procedures were clearly outlined, and measures were taken to prevent any breach of confidentiality or misuse of personal information.

Furthermore, oral consent was obtained from the interpreters featured in the images included in this paper, ensuring their voluntary participation in visual documentation.

This study was conducted in collaboration with one of the largest inclusive schools in Kazakhstan's capital, serving over 100 students with hearing impairments. The findings will inform the development and implementation of an accessible interactive tool based on the Digital Storytelling (DS) approach. In partnership with inclusive and special school administrations, this tool will be integrated into the educational process to enhance learning opportunities for deaf students. While this study utilized separate web pages for each lesson without integrating them into a unified platform, the project team intends to consolidate all session materials into a single platform following comprehensive feedback analysis from all stakeholders.

Future research should focus on expanding and refining the tool by incorporating artificial intelligence (AI)-driven personalization, allowing the content to dynamically adapt to students' proficiency levels and individual learning needs. Additionally, further studies could explore how age, gender, and language proficiency impact learning outcomes, providing deeper insights into optimizing inclusive educational strategies.

Beyond the context of deaf education, the Digital Storytelling (DS) approach developed in this study has the potential to benefit other special needs groups, including students with learning disabilities, attention disorders, or cognitive delays. The platform's multimodal features—such as visual narration, customizable pacing, and interactive tasks—can support diverse learning styles and provide alternative pathways for understanding abstract computer science concepts. Furthermore, the scalable design of StoryHub makes it adaptable to a wide range of educational settings and subject areas. With minor linguistic and cultural adaptations, the platform could be deployed in different regions or extended to other STEM disciplines.

VI. Conclusion

This study evaluated the effectiveness of a digital storytelling (DS) approach in enhancing computational thinking and digital literacy among middle school students with hearing impairments in computer science education. Quantitative results demonstrated a significant performance increase in the experimental group (mean post-test score: 76.4) compared to the control group (62.9), with statistical confirmation from the Mann-Whitney U test ($U = 290$, $p < 0.001$) and Wilcoxon signed-rank test ($W = 335$, $p < 0.001$). These findings confirm that DS is more effective than traditional methods in delivering STEM content to Deaf and Hard-of-Hearing (DHH) learners.

Beyond performance metrics, student engagement and autonomy improved significantly. Survey responses indicated heightened motivation, and interaction logs revealed a gradual reduction in reliance on teacher scaffolding—suggesting that students developed greater confidence and self-direction. These outcomes support the study's hypothesis that narrative-driven, multimodal learning environments can scaffold abstract computational concepts more effectively for students with visual and language-access needs.

The DS approach integrated sign language translation, visual storytelling, and interactive pacing, reflecting core principles of Universal Design for Learning (UDL). From a technological perspective, the modular, web-based structure of the platform makes it both accessible and scalable, with potential for easy adaptation across subjects, languages, and learner profiles.

While the results are promising, the study's limitations—including a single-site implementation, modest sample size, and short-term focus—warrant further research. Longitudinal studies are needed to evaluate long-term knowledge retention, and future work should explore AI-driven personalization to tailor learning to individual proficiency levels. Subgroup analyses based on age, gender, and sign language fluency could yield deeper insights into optimizing inclusive strategies.

In conclusion, this research highlights the transformative potential of digital storytelling in inclusive STEM education. By offering a scalable, visually immersive, and linguistically accessible learning model, it provides a practical framework for bridging educational gaps for DHH students. These findings offer actionable guidance for educators, developers, and policymakers in designing equitable and engaging computer science curricula for underrepresented learners.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Aigerim Kydyrbekova: Conceptualization, Methodology, Software Development, Data Collection, Writing-Original Draft Preparation. Anara Karymsakova: Formal Analysis, Investigation, Visualization. Akmet S. Dokuz: Conceptualization, Writing-Review and Editing. Gulmira Abildinova, Meruert Serik: Project Administration, Writing-Review and Editing. All authors have read and approved the final version of the manuscript.

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