Preparing Computer Science Teachers to Use Assistive Technologies with Students with Hearing Impairments

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***Abstract*—This study evaluates a practice-oriented model for preparing preservice computer science teachers to use assistive technologies and digital tools when teaching students with hearing impairments. The study addresses a persistent gap between general inclusive education courses and subject-specific preparation for accessible computer science instruction. A quasi-experimental mixed-methods design with a historical control group and triangulated validation was used. The experimental cohorts completed a 14-week module in which they analyzed access barriers in computer science lessons, compared assistive technologies such as automatic captioning and visual supports, applied WCAG-based accessibility checks, developed Google Colab notebooks, used generative AI tools with mandatory pedagogical verification, and produced case-based instructional solutions for deaf and hard-of-hearing learners. The total sample comprised 255 preservice computer science teachers, including 195 participants in the experimental group and 60 in the historical control group. Data were collected through an author-developed readiness questionnaire, expert evaluation of instructional products, and semi-structured interviews. The module was associated with stronger adjusted post-test readiness scores than baseline preparation. Expert-rated products and qualitative findings provided convergent evidence that participants became better able to connect accessibility barriers, technological choices, instructional design, and quality criteria in subject-specific teaching tasks. The study contributes a model of teacher readiness that treats assistive technology use not as general tool awareness, but as a set of observable professional actions in computer science teacher education. Because the comparison used a historical control group, the findings should be interpreted as intervention-associated changes in preservice teacher readiness rather than definitive causal evidence of classroom-level effectiveness.**

***Keywords*—assistive technology, Deaf and Hard-of-Hearing (DHH) education, computer science teacher education, accessibility, professional readiness, universal design for learning**

I. Introduction

School computer science education relies on terminological precision, orderly operations, and timely feedback during practical work. For Deaf and Hard-of-Hearing (DHH) students, these characteristics often become a persistent instructional barrier because a substantial part of classroom communication is transmitted through oral explanation, live commentary during demonstrations, and immediate verbal clarification while tasks are being completed. When access to the auditory channel is limited, the difficulty affects not only general comprehension of the topic but also the procedural integrity of learning. A missed instruction, an unclear term, or a delayed explanation may lead to errors in sequence, reduce learner independence, and increase reliance on repeated prompts. In this sense, the barrier is primarily didactic: it emerges at the intersection of subject content, lesson pacing, modes of presentation, and the organization of understanding checks.

Assistive technologies can reduce this barrier by transforming part of audio-mediated classroom communication into visually accessible formats and by stabilizing access to meaning during explanation and practice. In work with DHH learners, such tools may include automatic captioning, speech-to-text systems, visualized instructions, multimedia resources with sign-language support, and digital materials adapted to the perceptual characteristics of this group. At the same time, technological accessibility alone does not ensure educational effectiveness. A tool becomes pedagogically meaningful only when the teacher is able to match a specific technological solution to a learning objective, redesign instructions and teaching materials accordingly, and organize communication, practice, and assessment without lowering academic expectations. This requirement is especially important in computer science, where the logic of action, algorithmic structure, and terminological accuracy must be preserved rather than simplified.

Within preservice computer science teacher education, this issue is often manifested as a gap between general courses on inclusive education and technology-oriented digital training that remains detached from subject methodology and from the actual needs of DHH school students. In practice, effective preparation requires a subject-specific sequence: identifying the point at which access to meaning breaks down, selecting an appropriate assistive solution, designing accessible materials, implementing them in a teaching scenario, and evaluating the result against clear criteria. When this methodological linkage is absent, technology tends to be used episodically and with limited instructional effect, or support is reduced to task simplification rather than to meaningful accessibility.

The relevance of the study lies in the mismatch between current teacher preparation practices and the subject-specific

demands of computer science teaching for students with hearing impairments. Its scientific significance is connected with the shift from declarative support for inclusion to a measurable model of professional readiness defined through explicit criteria and indicators. Its practical significance lies in the development of a reproducible practice-oriented training model that can be integrated into university-based teacher education and later tested for transfer to school settings. In this study, transfer to authentic classroom practice and DHH students' learning outcomes are treated as important future validation targets rather than as outcomes measured directly in the present design.

Accordingly, this study pursued two connected objectives. The first objective was to develop and test a practice-oriented preparation model that links assistive technologies with concrete instructional decisions in computer science teaching for DHH learners. This objective directly responds to the gap between general inclusive education courses, technology-oriented digital training, and the subject-specific methodology required in accessible computer science instruction. The second objective was to evaluate whether a practice-based constructivist approach, including case analysis, active design, and the production of instructional artifacts, could improve preservice computer science teachers' readiness more effectively than baseline preparation based on more general exposure to inclusion and digital tools. In this study, professional readiness is operationally defined as an integrated combination of knowledge of DHH access barriers, applied instructional design skills, reflective evaluation, and the ability to connect technological solutions with specific computer science learning barriers. The study addressed the following research question: how does the proposed model affect preservice computer science teachers' readiness to design accessible computer science instruction for DHH learners according to the specified criteria and indicators? It was hypothesized that preparation integrating assistive technology training with accessible digital material design and rehearsal of typical computer science teaching scenarios would lead to higher levels of professional readiness than baseline preparation. The novelty of the study lies in operationalizing readiness to use assistive technologies as a system of subject-specific professional actions that can be purposefully developed and assessed. The proposed model connects the learning task and learning action with the access barrier, the presentation format, the technological solution, and the quality criteria used to evaluate teacher-produced instructional materials, accessibility decisions, and professional readiness indicators.

II. Literature Review

Recent research increasingly interprets Assistive Technologies (AT) not as isolated devices, but as part of a broader accessibility system in which technical tools are effective only when accompanied by needs assessment, user training, technical support, service infrastructure, and institutional responsibility. Within this perspective, the teacher becomes the central mediator between a learner's functional limitations, the demands of the instructional task, and the configuration of a particular technological solution. This shift is especially important for teacher education, because the main difficulty is no longer simply access to a tool, but the ability to make pedagogically justified decisions about when, why, and how that tool should be used in teaching practice [1–4].

Studies focusing on teacher preparation confirm that this mediating role remains underdeveloped. Preservice teachers generally express positive attitudes toward inclusion, yet these attitudes do not automatically translate into operational competence in the classroom [5–8]. In many cases, future teachers can identify or describe technologies, but experience difficulty embedding them into actual lesson scenarios, linking them to learning actions, anticipating their instructional consequences, and evaluating whether a chosen solution genuinely supports understanding. This distinction between declarative familiarity and operational readiness is critical. Research suggests that effective preparation is achieved not through theory-only exposure, but through case-based learning, micro-practice, structured decision-making tasks, and feedback on authentic instructional products. In other words, readiness develops when technology is taught as part of pedagogical action rather than as an external technical add-on [9–11].

In Deaf and Hard-of-Hearing (DHH) education, AT primarily address barriers related to spoken-language access, real-time participation, and the coordination of communication in classroom interaction. Frequently discussed solutions include hearing-assistance systems, real-time captioning, Automatic Speech Recognition (ASR), text duplication of oral instructions, visual supports, and multimedia materials designed for visually oriented information processing. However, the educational value of these solutions depends on more than their technical availability. Studies on real-time captioning and ASR show that latency, recognition errors, unstable terminology, and visually competing screen arrangements may increase cognitive load rather than reduce it. Better outcomes are observed when classroom interaction itself is adjusted through moderated turn-taking, explicit pacing, rephrasing, repeated comprehension checks, and deliberate management of visual attention. Thus, AT should be understood not as a substitute for pedagogical design, but as one of its components [12–15].

A similar conclusion emerges from research on digital learning environments. In online and blended settings, formal accessibility of platforms does not guarantee meaningful participation for DHH learners. Persistent barriers include missing or inaccurate captions, limited feedback channels, weak adaptation of assessments, and insufficient methodological guidance for teachers responsible for course delivery. For DHH students, access losses are often produced by seemingly routine instructional choices: audio-only explanations without text support, unmoderated synchronous discussions, videos without reliable subtitles, or interface designs that disregard visual processing strategies [16, 17]. These findings suggest that accessibility problems in digital environments are frequently instructional rather than purely technical and therefore require stronger methodological preparation of teachers [18, 19].

Subject-specific studies in computing education reinforce this point [20, 21]. Research on DHH learners' participation in computing shows that success depends not only on the presence of digital resources, but on the accessibility of

materials and interfaces, the coordination of terminology, the structure of instructions, and the organization of questioning, feedback, and practical task support. Reviews of technology integration in DHH education also point to fragmented implementation, inconsistent classroom transfer, and weak evaluation procedures for identifying pedagogical impact. The same limitation is evident in work on sign-language recognition and translation technologies: although such tools demonstrate technical promise, their transition from prototype to everyday educational use remains constrained by the absence of pedagogically grounded models of application [22–25].

Taken together, literature supports three conclusions that are directly relevant to this study. First, assistive technologies acquire educational value only when they are embedded in pedagogical support, user guidance, and institutional conditions that make their use sustainable. Second, DHH learners need more than text alternatives to speech; they need carefully structured communication, predictable visual information flow, and accessible digital environments in which instructions, demonstrations, feedback, and assessment are intentionally redesigned. Third, teacher preparation is more persuasive when it is practice-oriented, task-based, and connected to disciplinary demands rather than presented as a generic introduction to inclusive technologies. This point is especially important in computer science, where accessibility must preserve algorithmic sequence, terminological precision, and procedural completeness.

The remaining gap is therefore not the absence of assistive technologies themselves, but the limited development of subject-oriented preparation models that teach future computer science teachers how to use them in typical lesson situations: giving step-by-step instructions, organizing practical work, supporting group interaction, managing comprehension checks, adapting digital resources, and evaluating the accessibility of teacher-produced materials. Existing studies provide broad models of AT integration, general discussions of teacher preparedness, or separate DHH-focused technological solutions. Less is known about how these strands can be brought together in a coherent teacher education model for computer science. This gap provides the rationale for developing and empirically testing the practice-oriented model examined in the present study.

The study is grounded in three complementary theoretical perspectives. First, the TPACK framework explains why assistive technology preparation cannot be reduced to technical tool training. For a computer science teacher, effective use of AT requires the integration of technological knowledge, pedagogical knowledge, and subject content knowledge. In the present study, this means that students were not only introduced to captioning, speech-to-text systems, WCAG principles [26], Google Colab, and generative AI tools; they also had to connect these tools with concrete computer science learning actions, such as following an algorithmic procedure, interpreting code, completing a practicum task, or receiving feedback without relying on oral explanations [27].

Second, the model draws on Universal Design for Learning (UDL), particularly the idea that barriers should be addressed at the level of instructional design rather than treated only as individual learner deficits. In this study, UDL was operationalized through visual representation of instructions, text alternatives to oral explanations, structured digital resources, flexible ways of demonstrating understanding, and reduced dependence on the auditory channel. This was especially important for DHH learners because access to meaning in a computer science lesson often depends on the timing, format, and visibility of explanations [28, 29].

Third, the intervention followed a constructivist logic of professional learning. Readiness was expected to develop through active design, case analysis, reflection, and the production of instructional artifacts rather than through passive exposure to information about inclusion. Participants worked with authentic teaching situations, created accessible materials, tested the fit between a barrier and a technological solution, and justified their decisions. This approach treated teacher readiness as a developing, assessable construct rather than as a fixed attitude or a simple body of declarative knowledge [30]. This orientation is also consistent with project-based approaches to teacher preparation that link active project work, digital tools, reflection, and professional self-determination [31].

Methodologically, the study used a quasi-experimental mixed-methods design with triangulated validation. The quasi-experimental component made it possible to compare the experimental cohorts with a historical control group under conditions where random assignment was not feasible [32]. The mixed-methods component was used because professional readiness cannot be adequately captured through self-report alone. Questionnaire data were therefore interpreted together with expert-rated instructional products and qualitative interviews. This triangulation was intended to examine whether readiness scores were accompanied by observable product quality and more precise pedagogical reasoning [33]. Finally, because the value of an educational intervention depends partly on how consistently it is implemented, the study also considered implementation fidelity and completion indicators as part of the interpretation of results [34].

III. Materials and Methods

A. Study Design

The study used a quasi-experimental mixed-methods design with a historical control group and triangulated validation. The quasi-experimental component consisted of a pre-test/post-test comparison between cohorts that completed the newly designed practice-oriented module and historical control cohorts that had received baseline preparation without the integrated intervention. This design was selected because the intervention was implemented within an existing university teacher education program where full random assignment was not feasible.

The mixed-methods component was used to strengthen the interpretation of professional readiness. Quantitative questionnaire data were complemented by expert evaluation of instructional products and semi-structured interviews. The expert-rated products allowed us to examine whether self-reported readiness corresponded to observable performance in accessible instructional design. The

qualitative strand was used to clarify how participants understood accessibility barriers, assistive technology choices, and the transfer of training into future school practice. Thus, the design should be understood not only as a quasi-experimental comparison, but as a quasi-experimental study with triangulated mixed-methods validation.

The intervention model was developed to connect inclusive education principles with subject-specific instructional demands in computer science teaching. Rather than presenting assistive technologies as a general overview, the model was structured around typical pedagogical situations in which future teachers needed to identify an access barrier, select an appropriate technological solution, adapt instructional materials, and justify the instructional logic of their choices. This approach allowed readiness to be examined not only as knowledge about technologies, but also as the capacity to apply them in authentic teaching tasks.

B. Participants

The total sample comprised 255 preservice computer science teachers enrolled in teacher education programs. Of these, 195 participants formed the experimental group and 60 participants formed the historical control group. All participants were studying within a university-based teacher preparation program and had completed the core stages of subject-specific training relevant to school computer science instruction. The use of a historical control group made it possible to compare the outcomes of the revised training model with those obtained under the previous baseline format of preparation.

The participants represented the target population for whom the intervention was designed: future computer science teachers expected to work in inclusive school settings and to adapt digital instruction for learners with special educational needs, including students with hearing impairments. Participation in the study was voluntary. All students were informed about the educational and research purposes of the study, and only de-identified data were used in the analysis.

C. Intervention Module

The intervention consisted of a practice-oriented module designed to prepare preservice computer science teachers to use assistive technologies in instructional work with deaf and hard-of-hearing students. The module integrated four interrelated components: (1) identification of common communication and access barriers in computer science lessons; (2) selection of appropriate assistive and digital tools; (3) development of accessible instructional products; and (4) rehearsal of typical teaching scenarios in which these tools were pedagogically applied. The week-by-week module structure, task types, expected products, and assessment criteria are provided in Supplementary Material Appendix A (Tables A1–A3).

To make the theoretical logic of the intervention more explicit, Table 1 maps the main module components to TPACK and UDL principles and shows how these principles were operationalized in learning actions and study evidence.

Table 1. Mapping of the intervention module to TPACK and UDL principles

Module component	TPACK/UDL focus	Professional learning action	Evidence in the study
Identification of DHH access barriers in computer science lessons	PCK; UDL representation and access	Participants analyzed where oral explanation, terminology, task sequencing, or feedback could become inaccessible.	Barrier analysis tasks, case responses, interview themes
Selection of assistive and digital tools	TCK; TPK	Participants compared captioning, ASR, visual supports, WCAG-based checks, Google Colab, and AI-supported drafting in relation to specific learning barriers.	AT comparison tasks, WCAG audit, Colab design
Accessible instructional material design	TPACK integration; UDL representation and action/expression	Participants redesigned instructions, visualized algorithms, structured Colab notebooks, and reduced dependence on oral communication.	Colab notebooks, adapted instructions, expert ratings
Case-based rehearsal of teaching scenarios	TPK; PCK; constructivist professional learning	Participants justified pedagogical choices in realistic situations involving explanation, practicum work, feedback, and comprehension checks.	Case studies, expert ratings, qualitative themes
Reflective evaluation and verification	TPACK integration; UDL engagement; implementation fidelity	Participants checked AI outputs, evaluated accessibility decisions, and reflected on transfer barriers.	AI verification tasks, case rationales, interviews, fidelity indicators

Note: TPACK = Technological Pedagogical Content Knowledge; TCK = Technological Content Knowledge; TPK = Technological Pedagogical Knowledge; PCK = Pedagogical Content Knowledge; UDL = Universal Design for Learning.

Particular attention was given to the design of accessible digital materials for subject-specific instruction. Participants developed instructional solutions using Google Colab-based tasks, adapted explanations, visualized instructions, step-by-step supports, and other digital resources that could improve access to content and procedural understanding. The module also included applied case work focused on realistic school situations, such as explaining algorithmic procedures, organizing practical computer work, supporting comprehension during live demonstration, and maintaining accessibility without reducing academic demands.

The intervention was designed not as a purely technical introduction to assistive technologies, but as a structured model of professional action. Participants were required to justify why a chosen tool or adaptation matched a specific instructional problem and how that choice could support access to explanation, participation in practical work, and completion of subject-specific learning actions without relying primarily on oral communication.

D. Measures

The study used a mixed-methods assessment framework combining quantitative, expert-based, and qualitative data sources. This approach was chosen because professional readiness for assistive technology use is a multi-component construct: it includes knowledge of access barriers and tools, the ability to design accessible materials, reflective judgment about the quality and limits of technological solutions, and the capacity to justify pedagogical decisions. Relying on self-report alone would therefore have been insufficient. The questionnaire measured perceived readiness, expert-rated products assessed applied instructional performance, and

interviews helped interpret how participants connected technological choices with pedagogical reasoning.

The main quantitative instrument was an author-developed readiness questionnaire designed to assess preservice teachers' professional readiness to use assistive technologies in computer science instruction for students with hearing impairments. The questionnaire was developed in several stages. First, the authors specified the construct of readiness as four components: motivational-value, cognitive, operational, and reflective readiness. Second, an item pool was created to reflect the major instructional actions targeted by the intervention: identifying DHH access barriers, selecting assistive and digital tools, designing accessible computer science materials, and evaluating the quality and limitations of technological support. Third, the item set was reviewed by an expert panel for relevance, clarity, and coverage of the intended construct. A pilot test with 15 students was then used to check comprehensibility and response format. The final version included 25 Likert-scale items. Internal consistency was acceptable to strong across the total scale and component scales (Cronbach's $\alpha = 0.79–0.91$). The full item set, component structure, and scoring rules are reported in Supplementary Material Appendix B (Table B1). The instrument was administered before and after the intervention to enable comparison of readiness gains.

A second source of evidence was expert evaluation of the instructional products developed by participants in the experimental group. These products included Google Colab notebooks, adapted instructional materials, and case-based pedagogical solutions. Expert scoring made it possible to assess the extent to which participants could translate theoretical understanding into pedagogically sound and accessible subject-specific outputs.

The third source of evidence was a qualitative component based on semi-structured interviews. These materials were used to clarify how participants interpreted accessibility barriers, how they justified the use of specific assistive tools, and how they perceived the relationship between technological support and subject teaching.

E. Final Products and Quality Criteria

The final products developed by participants in the experimental group served as a performance-based indicator of readiness. These products were evaluated because they represented the applied outcome of the training module and provided evidence of whether participants could independently design accessible solutions for computer science teaching.

The product set included adapted Google Colab assignments, accessible lesson fragments, instructional scenarios, and case-based responses to typical teaching situations involving students with hearing impairments. The quality of these products was evaluated according to explicit criteria focused on pedagogical relevance, accessibility, accuracy of technological choice, clarity of instructional structure, and alignment between the identified learning barrier and the proposed solution. The scoring rubrics for the Colab notebook and the case study are provided in Supplementary Material Appendix C (Tables C1–C2).

Three expert evaluators assessed the instructional products. The panel included two university instructors with experience in computer science teaching methodology and digital learning resources and one practicing computer science teacher from a partner school with experience working with DHH learners. All products were anonymized and coded before scoring. The experts received rubric training, completed calibration on pilot submissions, and independently double-scored 20% of the products before reconciliation. Interrater reliability was estimated before adjudication and indicated good to excellent agreement. Details of expert composition, rater training, double scoring, adjudication, and ICC estimates are provided in Supplementary Material Appendix D (Tables D1–D3).

This approach made it possible to treat readiness not as an abstract declaration of confidence, but as demonstrable professional performance. The evaluation therefore emphasized the coherence of the instructional decision rather than the mere presence of a technological element.

F. Qualitative Component

To complement the quantitative and expert-based evidence, the study included a qualitative component aimed at clarifying how participants understood their own learning and professional development during the intervention. Semi-structured interviews were used to identify recurring themes related to accessibility, confidence, instructional decision-making, and the perceived usefulness of assistive technologies in subject teaching.

The qualitative strand was not intended as an independent phenomenological inquiry; rather, it served a triangulation function. It was used to interpret the mechanisms underlying the observed quantitative changes and to examine whether stronger scores were accompanied by more precise pedagogical reasoning, better articulation of subject-specific barriers, and more mature professional judgments about the use of assistive tools. The interview codebook, theme map, and theme prevalence are provided in Supplementary Material Appendix E (Tables E1–E3).

G. Procedure

Data collection followed a pre-test/post-test sequence. At the beginning of the study, participants completed the readiness questionnaire in order to establish baseline levels of professional preparedness. The experimental group then completed the practice-oriented intervention module, while the historical control group represented the outcomes of the previous training format without the integrated subject-specific intervention.

During the implementation phase, participants in the experimental group completed guided tasks, designed instructional products, and worked through subject-based cases requiring the use of assistive technologies in realistic teaching situations. These tasks were organized to move from identification of barriers to the development of concrete pedagogical solutions. After the intervention, participants completed the post-test administration of the readiness questionnaire. Final products were collected and submitted for expert evaluation. Qualitative materials were gathered after the main training activities had been completed.

H. Data Analysis

Quantitative data were analyzed using procedures

appropriate for a quasi-experimental pre-test/post-test comparison with a historical control group. Descriptive statistics were first used to summarize sample characteristics and baseline values. Reliability analysis was then applied to the readiness questionnaire to assess internal consistency across the total scale and component scales.

The primary intervention effect was estimated using ANCOVA, with post-test readiness as the dependent variable, group as the factor, and the corresponding pre-test score as the covariate. This approach was used to compare adjusted post-test outcomes while taking baseline readiness into account. For component-level outcomes, the same logic was applied to motivational-value, cognitive, operational, and reflective readiness. Effect sizes were interpreted alongside statistical significance in order to avoid relying on p values alone.

Expert ratings of instructional products were summarized as performance-based indicators of applied readiness. Associations between post-test readiness scores and expert-rated product quality were examined through correlation analysis in the intersection sample with both products available. These correlations were used as convergent evidence rather than as proof of direct causation. Qualitative materials were analyzed thematically. The final interpretation integrated questionnaire results, expert-rated products, implementation fidelity indicators, and interview themes in order to explain how the intervention functioned and where its inferential limits remained.

IV. Results and Discussion

A. Design Control and Baseline Equivalence

Before estimating the intervention effect, the comparability of the Experimental Group (EG) and the Historical Control Group (HCG) was examined at baseline. The descriptive profile of the sample and the initial readiness indicators are presented in Table 2. Overall, the two groups were broadly comparable in their starting positions, which supports the use of adjusted post-test comparisons as the main analytic strategy. Given the quasi-experimental design and the use of a historical control group, particular attention was paid to baseline values in order to reduce the risk of attributing pre-existing differences to the intervention itself.

Table 2. Demographic and baseline characteristics of the Experimental Group (EG) and Historical Control Group (HCG)

Variable	HCG (*n* = 60) M (SD) / *n* (%)	EG (*n* = 195) M (SD) / *n* (%)	Effect size
Age	21.2 (1.8)	21.4 (1.9)	SMD (d) = 0.11
Pre-test (overall readiness index)	2.08 (0.79)	1.94 (0.81)	SMD (d) = 0.17
Sex (women)	35 (58.3%)	119 (61.0%)	Cramer's V = 0.026
Degree level (Bachelor's)	18 (30.0%)	82 (42.1%)	Cramer's V = 0.119

"Degree level (Bachelor's)" reports Bachelor's students; the remaining participants were Master's students. We assessed practical baseline comparability using effect sizes: SMD (Cohen's d) for continuous variables and Cramer's V for categorical variables. The effect sizes indicate small baseline differences. Degree level showed the largest imbalance (V = 0.119); we considered this factor when interpreting artifact outcomes. Expanded comparison tables stratified by degree level and subsamples are reported in Supplementary Material Appendix F (Tables F1–F4).

The analytic logic of the study therefore focused not on raw post-test differences alone, but on post-intervention contrasts estimated with baseline readiness taken into account. This approach was important because the purpose of the study was to determine whether the practice-oriented training model produced stronger readiness gains than the baseline format of preparation rather than simply to describe end-point differences between two non-randomized cohorts.

B. Reliability and Validity of the Instrument

The internal consistency analysis showed that the readiness questionnaire demonstrated acceptable to strong reliability across its scales. The results are presented in Table 3. These findings support the use of the instrument for evaluating multiple dimensions of preservice teachers' readiness to use assistive technologies in computer science instruction for students with hearing impairments.

The reliability pattern is methodologically important for two reasons. First, it indicates that the questionnaire can be used not only as a general index of perceived readiness but also as a multidimensional instrument reflecting cognitive, operational, motivational-value, and reflective aspects of preparation. Second, it strengthens the interpretive basis for the subsequent outcome analysis, because observed post-test differences are less likely to be attributable to unstable measurement. In the context of this study, the instrument functioned as a structured diagnostic tool for identifying whether the intervention affected readiness as a complex professional construct rather than as a single undifferentiated attitude.

Table 3. Internal consistency of the readiness questionnaire scales

Readiness component	Items (k)	Cronbach's α
Motivational–value	5	0.84
Cognitive	8	0.91
Operational	8	0.88
Reflective	4	0.79
Overall readiness index	25	0.89

C. Primary and Secondary Outcomes

The primary outcome analysis demonstrated that the experimental group achieved stronger post-test results than the historical control group after adjustment for baseline values. The corresponding model estimates are presented in Table 4. Across the overall readiness index and its component dimensions, the intervention cohort showed a more favorable outcome pattern, indicating that the practice-oriented module was associated with greater gains than the baseline format of preparation.

The table reports adjusted post-test Estimated Marginal Means (EMM) and Standard Errors (SE) from ANCOVA models that controlled for the corresponding pre-test score (covariate). Partial η^2 indicates the proportion of variance in the outcome explained by the group factor after accounting for the covariate.

Table 4. ANCOVA results (EMM, F, p, partial η^2) for the overall readiness index and components

Outcome	HCG: adjusted M (SE)	EG: adjusted M (SE)	Difference (EG-HCG)	$F(1,252)$	p	partial η^2
Overall readiness	2.95 (0.05)	4.18 (0.03)	1.23	562.98	<0.001	0.691
Motivational-value	3.43 (0.05)	4.42 (0.03)	0.99	330.52	<0.001	0.567
Cognitive	2.35 (0.04)	4.06 (0.02)	1.71	1300.80	<0.001	0.838
Operational	2.67 (0.05)	4.09 (0.03)	1.42	651.79	<0.001	0.721
Reflective	2.52 (0.04)	4.16 (0.02)	1.64	1031.78	<0.001	0.804

These between-group differences are also illustrated by the adjusted post-test estimated marginal means shown in Fig. 1.

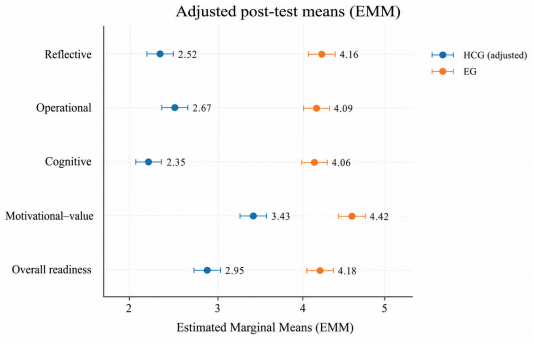


Fig. 1. Adjusted post-test Estimated Marginal Means (EMM) for overall readiness and its components in the Experimental Group (EG) and Historical Control Group (HCG).

As shown in Fig. 1, the experimental group demonstrated consistently higher adjusted post-test means across overall readiness and all measured components. This pattern suggests that the intervention affected readiness in a systematic rather than fragmented way. The gains were not limited to a single area of development; instead, they extended across understanding of accessibility barriers, the practical use of technological solutions, motivation to apply such tools in professional work, and the capacity for reflective pedagogical judgment.

From an educational perspective, this result is significant because it indicates that readiness to use assistive technologies develops more effectively when future teachers are trained through structured professional action. The observed advantage of the experimental group supports the assumption that a module built around authentic instructional tasks, accessible material design, and case-based rehearsal produces a stronger developmental effect than a baseline preparation format in which inclusive technologies are addressed in a more general or decontextualized manner.

At the same time, the magnitude of the adjusted effects should be interpreted cautiously. The partial η^2 values were large across all readiness components, especially for the cognitive, operational, and reflective components. This pattern is plausible because the module directly trained the knowledge and design actions measured by these scales, and the post-test was administered immediately after the intervention. The motivational-value component showed a comparatively smaller, although still substantial, effect. This difference is theoretically meaningful: attitudes and professional values are usually less sensitive to short-term instructional change than knowledge of tools, accessibility principles, and applied design procedures. The large effects should therefore be understood as strong intervention-associated differences in proximal readiness indicators, not as evidence that the model has already produced classroom-level effects for DHH students.

The historical control design also limits the strength of causal inference. The results show a consistent adjusted pattern in favor of the experimental cohorts, but they should not be read as equivalent to evidence from a randomized concurrent control design. Cohort-specific characteristics, broader changes in digital tool familiarity, instructor experience, and program-level changes may have contributed to the observed differences. For this reason, the outcome pattern is interpreted as evidence of an association between the practice-oriented module and higher readiness scores, supported by product-based and qualitative triangulation.

D. Performance-based Assessment of Instructional Products

The expert evaluation of instructional products provided an additional performance-based perspective on the intervention effect. The products created by participants in the experimental group included Google Colab notebooks, accessible lesson fragments, and case-based pedagogical solutions tailored to the needs of deaf and hard-of-hearing learners. The expert ratings are summarized in Tables 5 and 6.

The distinction between "acceptable" and "optimal" levels is important for interpreting the product scores. An acceptable product (≥8/12) was defined as a training-level artifact that contained the main accessibility features, a pedagogically relevant structure, and a generally appropriate match between the learning barrier and the selected technological solution. An optimal product (≥10/12) indicated a more coherent and independently usable artifact: accessibility adaptations were explicit, AI-supported content was verified, instructions were visually and procedurally clear, and practice tasks were testable and aligned with the intended learning action. However, "acceptable" should not be interpreted as equivalent to full readiness for unsupervised school implementation. Classroom use would still require adaptation to school infrastructure, learner profile, language context, and available support services.

Table 5. Expert ratings of Google Colab-based instructional products

Indicator	M (SD)	Median (IQR)	% at maximum
Use of AI (0–3)	2.8 (0.4)	3.0 (3.0–3.0)	—
Accessibility adaptation (0–3)	2.9 (0.3)	3.0 (3.0–3.0)	—
WCAG 2.1 compliance (0–2)	1.9 (0.5)	2.0 (2.0–2.0)	—
Code comments (0–2)	2.0 (0.5)	2.0 (2.0–2.0)	—
Practice tasks (0–2)	1.7 (0.6)	2.0 (2.0–2.0)	—
TOTAL SCORE (0–12)	10.2 (1.5)	10.0 (10.0–11.0)	15.8% (29/183)

Note: Thresholds: Acceptable ≥ 8/12; Optimal ≥ 10/12. Threshold shares are reported for the total score: Optimal 93.4% (171/183); Acceptable 98.9% (181/183). All percentages are calculated from the number of rated submissions (n = 183).

The expert assessment showed that the participants were able to translate readiness into concrete instructional outputs rather than merely report positive self-perceptions. This is a particularly important result because a central limitation of self-report measures is that they may overestimate

competence when respondents recognize desirable pedagogical principles but cannot yet implement them in practice. In contrast, the instructional products developed in the experimental group provided observable evidence of applied readiness.

Table 6. Expert ratings of case-based instructional solutions

Indicator	M (SD)	Median	% at maximum	% ≥10 (Optimal)	% ≥8 (Acceptable)
Pedagogical reasoning (0–4)	3.1 (0.8)	3.0	—	—	—
Use of AI-based solutions (0–4)	3.2 (0.7)	3.0	—	—	—
Adaptability analysis (0–4)	2.8 (0.9)	3.0	—	—	—
TOTAL SCORE (0–12)	9.1 (2.1)	9.0	4.5% (8/178)	78.1% (139/178)	91.0% (162/178)

Note: We rated 178 case studies; 17 participants submitted only the Colab notebook and were excluded from case-study calculations. Thresholds: Acceptable ≥ 8/12; Optimal ≥ 10/12. All percentages are calculated from the number of rated case studies (n = 178). Interrater reliability was high; detailed ICC estimates are reported in Supplementary Material Appendix D (Table D3).

The associations between questionnaire-based readiness outcomes and the expert-rated quality of the two product formats are presented in Fig. 2.

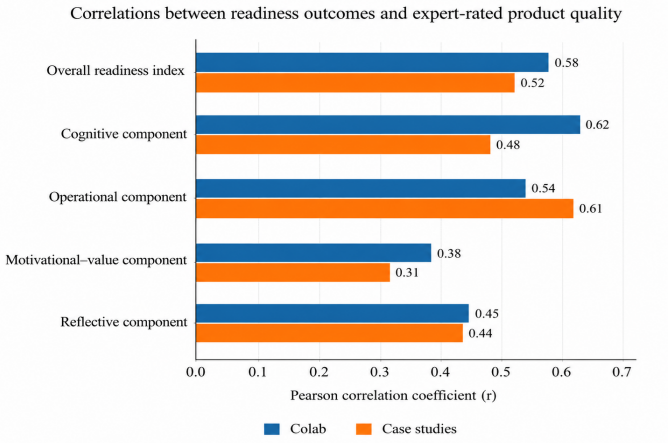


Fig. 2. Correlations between questionnaire-based readiness outcomes and expert-rated quality of Google Colab notebooks and case-based solutions.

As shown in Fig. 2, cognitive readiness was most strongly associated with Google Colab notebook quality (r = 0.62), whereas operational readiness was most strongly associated with case-study quality (r = 0.61). The motivational-value component showed the weakest associations with both product types, while reflective readiness showed similar moderate associations with Colab and case-study quality.

This pattern should not be interpreted as a contradiction. Rather, it suggests that different product formats make different aspects of readiness more visible. A technically structured product such as a Colab notebook is well suited for demonstrating coherence of instructional design, clarity of sequencing, and explicit adaptation logic. By contrast, a case-based response more directly elicits professional judgment in dynamic pedagogical situations. Taken together, the two forms of assessment offer a fuller picture of readiness than either one could provide alone.

E. Associations between Readiness and Artifact Quality

To examine whether questionnaire-based readiness was meaningfully related to practical performance, associations between post-test readiness scores and expert ratings of instructional products were analyzed. The results are presented in Table 7.

Table 7. Associations between readiness outcomes and expert-rated instructional product quality

Questionnaire variable	r (Colab)	r (Case studies)	p
Overall readiness index	0.58	0.52	<0.001
Cognitive component	0.62	0.48	<0.001
Operational component	0.54	0.61	<0.001
Motivational–value component	0.38	0.31	<0.001
Reflective component	0.45	0.44	<0.001

Note. Correlations were computed on the intersection sample with both artifacts available (n = 178). p-values are two-tailed.

The correlations ranged from moderate to strong, which clarifies the relationship between self-reported readiness and observable product quality. The strongest association was found between the cognitive component and Colab quality (r = 0.62), suggesting that participants who reported stronger knowledge of accessibility principles, assistive technologies, and digital tools tended to produce more coherent accessible notebooks. The operational component was most strongly associated with case-study quality (r = 0.61), which is theoretically consistent because case tasks required participants to make situated pedagogical decisions rather than simply demonstrate tool familiarity. The motivational-value component showed weaker, although still statistically significant, associations with both product types (r = 0.38 for Colab and r = 0.31 for case studies). This lower association is expected: positive attitudes toward inclusion do not necessarily guarantee the ability to produce high-quality accessible instructional materials.

These findings support the internal coherence of the assessment model. They do not prove that readiness scores directly caused better product quality, but they show that the questionnaire results were not detached from externally rated instructional performance. In methodological terms, this convergence strengthens the interpretation of the intervention-associated gains because self-report, product-based assessment, and qualitative evidence point in the same general direction.

F. Implementation of Fidelity and Qualitative Findings

Implementation of fidelity evidence indicated that the intervention was delivered in accordance with its intended structure and that participants completed the sequence of activities linking accessibility analysis, technological choice, product design, and case-based rehearsal. Fidelity indicators and threshold attainment are reported in Supplementary Material Appendix A (Table A3). This procedural consistency is important because it allows the observed outcome pattern to be interpreted in relation to the intervention model as designed rather than as an accidental by-product of irregular delivery.

The qualitative findings complemented the quantitative and expert-based results by showing a clear shift in how participants understood inclusive subject teaching. At the beginning of training, readiness was often framed in broad and generalized terms, with assistive technologies described as helpful tools in a largely abstract sense. By the end of the

intervention, participants more frequently articulated readiness through specific pedagogical actions: identifying where access to meaning breaks down, selecting an appropriate support format, restructuring explanations, adapting visual materials, and preserving the academic integrity of computer science tasks. The coded themes and their prevalence are reported in Supplementary Material Appendix E (Table E3).

To make the access-barrier dimension more explicit, Table 8 summarizes the main types of barriers that participants addressed in their artifacts, case responses, and interviews. This table is descriptive and integrative rather than a separate pre/post statistical outcome; its purpose is to clarify how the training model supported more precise identification of barriers in computer science instruction.

Table 8. Categories of DHH access barriers addressed in participant artifacts and qualitative data

Barrier category	How the barrier appears in computer science instruction	Evidence of more precise identification after the module
Linguistic and terminological barriers	Key terms, commands, error messages, and teacher explanations may be missed or misunderstood when they are delivered mainly through oral speech.	Participants more often specified which terms, code-related expressions, or explanation segments required written, visual, or captioned support.
Procedural and algorithmic barriers	A missed step in an algorithm, coding demonstration, or practicum instruction can disrupt the whole learning action.	Participant products increasingly used step-by-step written instructions, visual sequencing, code comments, and structured Colab cells.
Visual-attentional barriers	DHH learners may need to divide attention between the teacher, screen, captions, interpreter, peer interaction, and task materials.	Participants more frequently redesigned the visual layout of materials and reduced unnecessary switching between oral explanation and screen-based work.
Social-interactive barriers	Group work, questioning, immediate clarification, and peer discussion may exclude DHH learners if turn-taking and communication rules are not structured.	Case responses more often included moderated turn-taking, written feedback channels, comprehension checks, and explicit communication rules.
Feedback and assessment barriers	Oral feedback, rapid correction, and unclear assessment criteria may make it difficult for DHH learners to monitor progress independently.	Participants more often proposed written feedback, visible success criteria, rubrics, and task checkpoints aligned with the learning action.
Technological reliability barriers	ASR, captioning, AI-generated explanations, and digital tools can introduce errors, latency, or inaccurate terminology.	Participants increasingly emphasized verification of AI outputs, checking caption accuracy, and preserving teacher responsibility for final pedagogical decisions.

Note: The categories synthesize patterns observed in instructional artifacts, case-based responses, and interview themes. They should not be interpreted as direct measures of DHH students' classroom outcomes.

A second qualitative pattern concerned the relationship between technology and pedagogy. Participants increasingly recognized that accessibility is not achieved by simply adding captions, text, or digital tools to an existing lesson. Instead, they described the need to redesign the instructional sequence itself, including pacing, terminology presentation, demonstration logic, and comprehension checks. This shift is especially relevant for computer science instruction, where procedural clarity and the ordering of actions are central to successful learning.

A third qualitative pattern concerned professional confidence. Participants did not merely report feeling more prepared; they described greater certainty in deciding which technological supports were appropriate for particular lesson situations. This distinction between general confidence and situationally grounded professional judgment is important because it suggests that the intervention contributed to a more mature form of readiness tied to decision-making rather than to attitude alone.

G. Integrated Discussion of Findings

The results suggest that the proposed training model was associated with a meaningful improvement in preservice computer science teachers' readiness to use assistive technologies when designing instruction for students with hearing impairments. This interpretation is supported by three convergent lines of evidence: stronger adjusted post-test outcomes in the experimental group, expert-rated instructional products that met acceptable or optimal quality thresholds, and qualitative indications of more precise pedagogical reasoning. Convergence is important because readiness in this study was not treated as attitude alone. It was examined as a combination of knowledge, applied design skill, reflective judgment, and the ability to connect a technological solution with a specific computer science learning barrier.

The central contribution of the study lies in showing that readiness develops more effectively when assistive technology training is embedded within subject-specific instructional action. The intervention did not treat accessibility as an external supplement to inclusive education theory. Instead, it linked the learning barrier, the instructional goal, the technological support, and the quality criteria of the final pedagogical product. This structure appears to explain why the observed gains extended across multiple components of readiness rather than remaining limited to awareness or attitude.

The TPACK/UDL mapping also clarifies why the intervention was not limited to technical familiarization. Tool knowledge was first separated analytically from pedagogical decision-making: participants learned what captioning, ASR, WCAG-based checks, Google Colab, and AI-supported drafting could do, but they also had to explain when these tools were pedagogically appropriate, what access barrier they addressed, and how they preserved the logic of a computer science task. This distinction is important because accessibility in computer science requires simultaneous attention to technology, subject content, lesson procedure, and learner access.

These findings are consistent with broader research suggesting that assistive technologies become educationally meaningful only when integrated into pedagogical decision-making [1–4, 9–11, 22–25]. The present study adds a more specific contribution by demonstrating how this principle can be operationalized in computer science teacher education. In this subject area, instructional success depends heavily on sequencing, terminological precision, and procedural comprehension. For deaf and hard-of-hearing

learners, these features can become points of exclusion unless teachers deliberately redesign the lesson to preserve access to meaning. The intervention addressed exactly this point, which may explain the stronger readiness pattern observed in the experimental group.

The performance-based findings are particularly important. In many teacher education studies, claims about preparedness rest primarily on self-report instruments [9–11]. In contrast, the present study incorporated expert evaluation of participant-generated products and showed that stronger readiness was reflected in concrete instructional outputs. This strengthens the practical relevance of the results and supports the argument that the intervention influenced not only what participants said they knew, but also what they were able to produce and justify.

The qualitative strand further clarifies the mechanism behind this effect. Participants increasingly moved from a generalized understanding of inclusion toward a more operational view in which accessibility was treated as a property of instructional design. This shift suggests that the intervention functioned not only as a knowledge-building module but also as a framework for reorganizing professional thinking. In other words, participants did not simply accumulate information about available technologies; they learned to view computer science teaching itself through the lens of access, representation, communication, and evaluative alignment.

The historical control design also requires a more explicit discussion of rival explanations. Although the baseline indicators were broadly comparable, the groups were not randomly assigned. Part of the observed difference may therefore reflect cohort-specific factors, accumulated instructor experience, changes in program climate, or broader changes in students' familiarity with digital and AI-supported tools over time. Selection-related factors also cannot be fully excluded, especially because the experimental and historical cohorts belonged to different academic years. A further source of caution concerns degree level: the proportion of Bachelor's and Master's students was not identical across groups, and Master's students in the experimental cohort performed better on the case-study task. These factors do not invalidate the observed pattern, especially because baseline readiness was controlled statistically, but they prevent a strong causal claim. The findings should therefore be interpreted as evidence of an intervention-associated improvement supported by triangulated indicators, not as definitive proof of effectiveness under all conditions.

At the same time, the results should be interpreted within the limits of the design. The use of a historical control group does not allow causal inference at the same level as a randomized controlled study. In addition, the study was conducted within one institutional training context, which may limit the generalizability of the findings to other teacher education settings. Nevertheless, the convergence of quantitative, expert-based, and qualitative evidence provides a sufficiently coherent basis for concluding that the proposed model is promising and educationally meaningful.

H. Summary of Findings

The major findings of the study are summarized in Table 9.

Table 9. Summary of key findings

Indicator	Result	Interpretation
Primary outcome (overall readiness, ANCOVA)	$F(1,252) = 562.98$, $p < 0.001$, partial $\eta^2 = 0.691$	Large intervention effect after adjusting for baseline
EMM (post-test), HCG vs EG	HCG: 2.95 (SE = 0.05); EG: 4.18 (SE = 0.03)	EG shows a higher adjusted post-test level
Adjusted difference (EG–HCG)	1.23	EG advantage on the 1–5 scale after pre-test adjustment
Largest component effect	Cognitive: partial $\eta^2 = 0.838$	Strongest impact on knowledge/instrumental competence
Performance-based evidence (artifacts)	Colab: M = 10.2/12 (SD = 1.5); Case studies: M = 9.1/12 (SD = 2.1)	Gains are supported by product-based assessment
Interrater agreement	ICC = 0.87 (Colab); ICC = 0.82 (cases)	High reliability of expert ratings
Triangulation	$r = 0.58$ (Colab); $r = 0.52$ (cases), $p < 0.001$	Self-report aligns with product-based outcomes

Note. All primary-outcome conclusions rely on a single ANCOVA specification and are consistent across Table 4 and Fig. 1 (no alternative sets of end-point statistics are introduced in the narrative).

Overall, the study suggests that preservice computer science teachers' readiness to work with deaf and hard-of-hearing students can be strengthened through a model that combines assistive technology training with subject-specific instructional design, performance-based assessment, and rehearsal of authentic classroom situations. The results support the view that preparation for inclusive digital teaching should go beyond general awareness of accessibility issues. It requires a structured professional logic in which technological tools are selected, adapted, and evaluated in direct relation to the pedagogical demands of the lesson.

I. Limitations and Future Research

The design of this study allowed the model to be examined in a real teacher education setting, but it also sets clear limits on interpretation. The comparison was made with a historical control group rather than with a concurrent randomized group. Baseline checks and ANCOVA helped reduce some validity threats, yet they cannot fully rule out cohort differences, changes in instructor experience, selection-related factors, or the possibility that later cohorts were generally more familiar with digital and AI-supported tools. For this reason, the findings are best read as a consistent pattern associated with the revised module, not as strong causal proof in the same sense as a randomized trial.

Another limitation concerns the level at which outcomes were measured. The study focused on preservice teachers' readiness and on the quality of the instructional products they created. It did not follow graduates into school classrooms, and it did not collect learning outcomes from DHH students. This means that the results show improvement in a proximal teacher-preparation outcome: readiness to design accessible computer science instruction. They do not yet show whether this readiness leads to better participation, understanding, or achievement among DHH learners in everyday classroom

conditions.

The timing of measurement also matters. The post-test was administered immediately after the module, when the training experience was still recent and participants had just completed their final products. It remains unknown whether the same level of readiness would be sustained after several months or after graduates begin working in schools. Some aspects of readiness may be more fragile than others. Operational and reflective skills, for example, may depend heavily on whether a school provides enough time, technical infrastructure, captioning or ASR access, and methodological support. The motivational-value component also deserves further attention, because long-term implementation may depend not only on skill but also on professional commitment. Long-term transfer may also depend on opportunities to apply newly developed skills and on support within the professional environment [35].

The study was conducted in one university-based teacher education context. This limits external validity. The model may need adjustment in institutions with different language policies, cultural expectations about inclusion, levels of digital infrastructure, access to DHH support services, or teacher experience with assistive technologies. Future studies should therefore examine how the model works under different institutional and regional conditions and whether factors such as teacher digital competence, school resources, class size, language of instruction, and prior contact with DHH learners moderate its impact.

Further research should move beyond immediate readiness indicators. Useful next steps would include delayed follow-up, concurrent comparison groups, classroom observation, and direct indicators of communication quality, visual instruction design, use of captioning or ASR, peer interaction, feedback accessibility, and learner participation. Where ethically and practically feasible, future studies should also test whether stronger preservice teacher readiness translates into measurable benefits for DHH students in authentic computer science classrooms.

V. Conclusion

This study addressed a practical and methodological gap in computer science teacher education: general inclusion courses and general digital-skills training do not sufficiently prepare future teachers to make computer science lessons accessible for DHH learners. The proposed practice-oriented module responded to this gap by linking assistive technologies with concrete instructional decisions: how to present terminology, how to structure coding tasks, how to reduce dependence on oral explanation, how to organize accessible feedback, and how to evaluate the accessibility of digital resources.

The findings show that the module successfully strengthened preservice teachers' readiness to design accessible computer science instruction. Compared with the historical control group, the experimental group demonstrated substantially higher adjusted post-test readiness scores. This indicates that preparation based on case analysis, active design, and the production of instructional artifacts was more effective than baseline preparation in which inclusion and digital tools were addressed in a more general and less subject-specific way.

The study also shows that readiness developed most strongly when assistive technology was treated as part of pedagogical action rather than as a separate technical add-on. The largest improvements were found in components closely connected with the module content, especially knowledge of accessibility tools and the operational design of accessible materials. Expert-rated products and qualitative findings confirmed that participants were better able to connect access barriers, technological choices, instructional structure, and quality criteria in concrete computer science teaching tasks.

The main contribution of the study is therefore a subject-oriented model for preparing and assessing future computer science teachers' readiness to use assistive technologies with DHH learners. Readiness, in this model, is not limited to familiarity with tools. It includes knowledge of DHH access barriers, applied design skills, reflective evaluation, and the ability to match a technological solution with a specific computer science learning problem. In this sense, the module provides a more systematic way to move from general inclusive intentions to observable professional actions.

The conclusions remain bounded by the research design. The study measured preservice teacher readiness and teacher-produced instructional products; it did not measure DHH students' learning outcomes or observe graduates in authentic school classrooms. The historical control design also limits the strength of causal inference. Nevertheless, within these boundaries, the evidence supports the conclusion that the practice-oriented model addressed the identified preparation gap and improved the readiness of preservice computer science teachers for accessible instructional design. Future research should examine whether this readiness is sustained over time and whether it leads to measurable benefits for DHH learners in real computer science classrooms.

Ethical Approval and Informed Consent

According to the determination of the Ethics Committee of Sarsen Amanzholov East Kazakhstan University, this study qualified as minimal-risk pedagogical research involving adult participants and did not require formal prior ethics committee approval under the applicable institutional policy (Protocol No. 124, dated "11" March 2026). Participation in the study was voluntary, and informed consent was obtained from all participants prior to data collection and for the use of de-identified instructional and assessment materials for research purposes. No personally identifiable information was included in the dataset, interview materials, or reported results.

Declaration on the Use of AI Tools

The authors used AI-based language tools only for language polishing, clarity checking, and minor editorial refinement. These tools were not used to generate research data, conduct statistical analysis, create empirical results, or make scientific interpretations. All substantive content, data analysis, conclusions, and revisions were reviewed and approved by the authors, who take full responsibility for the final manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Meiirzhan Roman: Conceptualization, investigation, data curation, formal analysis, writing—original draft preparation. Saltanat Adikanova: Methodology, supervision, validation, writing—review and editing. Balgyn Dildebay: Methodology, resources, software, writing—review and editing. Ainagul Kadyrova: Validation, formal analysis, writing—review and editing. Saniya Kubentayeva: Validation, supervision, writing—review and editing. Zhanat Seitakhmetova: Data curation, visualization, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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