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PAPER

Optimising Dyslexia Intervention Leveraging a Mobile Adaptive Multi-Sensory AI Model with Real-Time Speech Analytic

Resmi Darni[1](✉), Yulyanti Harisman[1], Lili Dasa Putri[1], Efi Fitriana[2], Rezki Ashriyana Sulistiobudi[2], Andhika Herayono[1]

[1]Universitas Negeri Padang, Padang, Indonesia

[2]Universitas Padjadjaran, Bandung, Indonesia

resmidarni@ft.unp.ac.id

ABSTRACT

Phonological dyslexia is a neurodevelopmental learning disorder characterised by persistent difficulties in phoneme–grapheme mapping, phonological decoding, and pronunciation accuracy. Conventional dyslexia interventions are often non-adaptive, therapist-dependent, and limited in scalability, reducing their effectiveness in inclusive education contexts. This study aims to develop and evaluate a mobile adaptive multi-sensory artificial intelligence (AI) model integrated with real-time speech analytics to optimise phonological dyslexia intervention. The study employed a research and development (R&D) approach using the ADDIE framework, combined with a quasi-experimental pre- and post-test control group design. Participants were elementary school learners diagnosed with phonological dyslexia. The proposed system integrates multi-sensory phonological training, adaptive difficulty adjustment, and real-time speech analytics to provide immediate feedback and personalised learning pathways. Data were collected through expert validation, usability questionnaires, phonological reading tests, and speech analytics metrics, including phoneme error rate (PER) and word error rate (WER).

KEYWORDS

phonological dyslexia, adaptive artificial intelligence (AI), speech analytics, mobile learning, cognitive rehabilitation

1 INTRODUCTION

Phonological dyslexia is one of the most prevalent cognitive reading disorders among primary school children worldwide [1]. This neurobiological condition is characterised by significant difficulties in associating sounds (phonemes) with letter symbols (graphemes), which ultimately hinders reading fluency

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and comprehension. The prevalence of this disorder reaches 7–10% of the global population, making it a critical issue that, if left unaddressed, can trigger academic decline, low self-esteem, and an increased risk of school dropout [2]. In Indonesia, the provision of rehabilitation services for dyslexic students still faces major challenges, particularly regarding the limited number of expert therapists and the minimal utilisation of artificial intelligence-based technology within inclusive education. Phonological dyslexia is a specific neurodevelopmental learning disorder characterised by persistent difficulties in phoneme awareness, phoneme–grapheme correspondence, and decoding unfamiliar words, despite adequate intelligence and educational exposure [3]. This condition represents one of the most prevalent forms of dyslexia, particularly among elementary school learners, with reported global prevalence rates ranging from 7% to 10%. Learners with phonological dyslexia typically struggle to recognise and manipulate speech sounds, leading to slow, inaccurate reading and reduced comprehension. If not addressed through effective intervention, these difficulties may persist into adolescence and adulthood, negatively affecting academic achievement, psychological well-being, and long-term socio-economic outcomes [4]. While such approaches may yield improvements, they are frequently constrained by limited availability of trained specialists, high intervention costs, and low scalability. Moreover, conventional methods tend to apply uniform training strategies, offering minimal personalisation and delayed feedback, which may reduce learner engagement and limit cognitive rehabilitation effectiveness [5].

Recent advancements in educational technology and artificial intelligence (AI) have opened new possibilities for addressing these limitations [6]. In particular, speech-based technologies such as text-to-speech (TTS) and speech-to-text (STT) systems have been increasingly explored to support phonological awareness and reading development [7]. Several digital interventions and serious games for dyslexia have demonstrated that auditory stimulation and interactive feedback can improve phoneme recognition and reading fluency. However, many existing systems remain non-adaptive, providing fixed levels of difficulty regardless of individual learner progress and offering limited real-time analysis of phonological errors [8]. Research in cognitive rehabilitation and learning sciences consistently emphasises that adaptive training, immediate feedback, and personalised scaffolding are essential for strengthening phonological processing pathways in the brain [9].

Speech analytics, supported by AI-based signal processing and pattern recognition, offers a promising solution to this challenge [10]. By analysing acoustic features such as phoneme accuracy, articulation duration, and error patterns, speech analytics enables objective, real-time assessment of learners' pronunciation performance. When integrated into an adaptive learning system, these analytics can drive automatic adjustment of task difficulty, selection of appropriate stimuli, and delivery of corrective feedback tailored to individual needs [11]. Inclusive education services often face shortages of specialised therapists and lack digital tools designed specifically for phonological rehabilitation [12]. However, for mobile interventions to be effective, they must move beyond static content delivery and incorporate adaptive, data-driven rehabilitation models [13]. To address these challenges, this study proposes a Mobile Adaptive Multi-Sensory AI Model with Real-Time Speech Analytics designed to optimise dyslexia intervention for learners with phonological dyslexia. The proposed model integrates auditory simulation through TTS, real-time speech analytics using STT and phonological error detection, and an adaptive self-training engine that dynamically adjusts training difficulty based on learner performance. By combining visual, auditory, and interactive feedback, the system aims to strengthen phonological awareness while reducing cognitive overload and increasing learner autonomy [14].

Furthermore, the inclusion of monitoring features allows teachers and therapists to track learner development and adjust intervention strategies when necessary. The novelty of this study lies in the integration of four key elements within a single mobile platform: (1) adaptive self-training logic, (2) multi-sensory phonological stimulation, (3) real-time speech analytics, and (4) inclusive, learner-centred design. To the best of our knowledge, this study represents one of the first efforts in Indonesia to develop and empirically evaluate a mobile AI-based adaptive model specifically targeting phonological dyslexia rehabilitation [15]. Accordingly, the objectives of this study are threefold: (1) to develop a valid and practical mobile adaptive multi-sensory AI model for phonological dyslexia intervention, (2) to implement the model within a user-friendly mobile application integrated with real-time speech analytics, and (3) to evaluate the effectiveness of the proposed system in improving phonological reading performance among elementary school learners with dyslexia. By achieving these objectives, this study seeks to contribute both theoretically and practically to the fields of inclusive education, educational technology, and AI-assisted cognitive rehabilitation [16].

2 MATERIALS AND METHODS

2.1 Research design

This study adopted a developmental–experimental research design integrating Research and Development (R&D) with a quasi-experimental approach. The design was selected to address two primary objectives: developing a mobile adaptive multi-sensory AI model for phonological dyslexia intervention and empirically evaluating its effectiveness. The ADDIE framework guided the development process, while a pretest–posttest control group design assessed intervention outcomes [17]. The R&D approach enabled a systematic process of designing, implementing, and refining the proposed intervention model to ensure alignment with pedagogical principles, cognitive rehabilitation theory, and technological feasibility. The ADDIE framework, consisting of the analyse, design, develop, implement, and evaluate phases, was employed due to its flexibility, iterative structure, and widespread use in educational technology research, particularly for adaptive and learner-centred systems. To evaluate the effectiveness of the developed model, a quasi-experimental pretest–posttest control group design was embedded within the R&D framework [18]. This design facilitated a direct comparison of phonological reading outcomes between learners who used the adaptive AI-based intervention (experimental group) and those who received conventional phonological instruction (control group). By integrating experimental evaluation into the development process, the study moves beyond product development and provides empirical evidence of learning impact [19]. The overall research design integrating the R&D approach, the ADDIE framework, and the quasi-experimental design is illustrated in Figure 1.

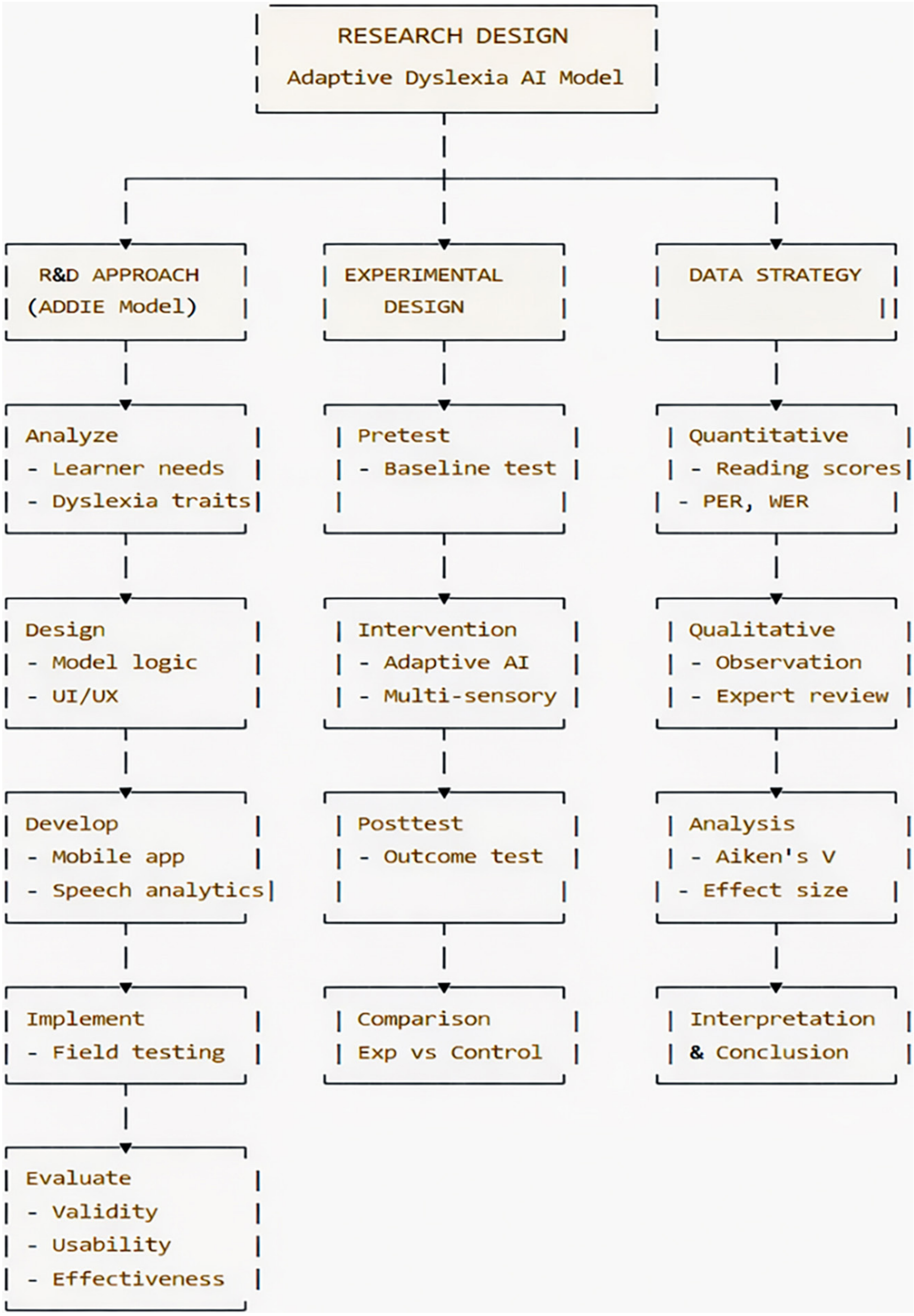

Fig. 1. Research design mind map

The research design emphasises adaptive cognitive rehabilitation, in which intervention difficulty is dynamically adjusted based on learners' real-time performance derived from speech analytics. This design is particularly suitable for phonological dyslexia, a condition characterised by heterogeneous error patterns and varying levels of phonological processing deficits. By integrating adaptive system development with controlled effectiveness testing, the research design ensures both internal validity and practical relevance within inclusive education contexts [20]. The key components of the research design, including the research type, development model, experimental design, variables, participants, and data types, are summarised in Table 1.

Table 1. Research design framework

Component	Description
Research Type	R&D combined with quasi-experimental design
Development Model	ADDIE
Experimental Design	Pre- and post-test control group
Independent Variable	Mobile adaptive AI-based dyslexia intervention
Dependent Variables	Phonological accuracy, phoneme error rate
Participants	Elementary learners with phonological dyslexia
Data Types	Quantitative and qualitative

2.2 Participants and research setting

The participants of this study consisted of elementary school learners diagnosed with phonological dyslexia, selected using a purposive sampling technique. Participant selection was carried out in collaboration with professional therapists and inclusive education practitioners to ensure that all learners met established diagnostic criteria for phonological dyslexia. These criteria included persistent difficulties in phoneme awareness, phoneme–grapheme correspondence, and phonological decoding [21].

A total of 20 learners participated in the field implementation phase. Participants were divided into an experimental group receiving the adaptive AI-based intervention and a control group following conventional phonological instruction. All participants had normal or above-average intelligence and no sensory impairments. The study was conducted in two main settings. The first was the Educational Technology Development Laboratory at Universitas Negeri Padang, which supported system development and technical validation. The second was the Inclusive Education and Disability Service Unit of Padang City, serving as the field implementation site [22]. The demographic and educational characteristics of the research participants, including age range, grade level, dyslexia type, and group assignment, are presented in Table 2.

Table 2. Characteristic of research participants

Characteristic	Description
Total participants	20 learners
Age range	7–10 years
Grade level	Grades 2–4
Dyslexia type	Phonological dyslexia
Experimental group	10 learners
Control group	10 learners

2.3 Development procedure (ADDIE model), data collection and data analysis

To guide the systematic development of the proposed mobile adaptive multi-sensory AI intervention, this study adopted the ADDIE instructional design model, which consists of five iterative phases: analyse, design, develop, implement, and evaluate. The ADDIE model was selected due to its structured yet flexible nature, making it particularly suitable for educational technology research that integrates pedagogical design, cognitive rehabilitation principles, and artificial intelligence–based systems. In the Analysis phase, learner characteristics, phonological dyslexia profiles, and limitations of existing intervention approaches were identified through literature review, field observations, and expert consultations [23]. The Design phase focused on constructing the adaptive learning architecture, defining system work-flows, and developing user interface and interaction designs tailored to learners with dyslexia. During the Develop phase, the conceptual design was implemented into a functional mobile application integrating speech analytics, auditory simulation, and adaptive training mechanisms [24]. The systematic development procedure of the proposed mobile adaptive multi-sensory AI intervention, following the ADDIE instructional design model, is illustrated in Figure 2.

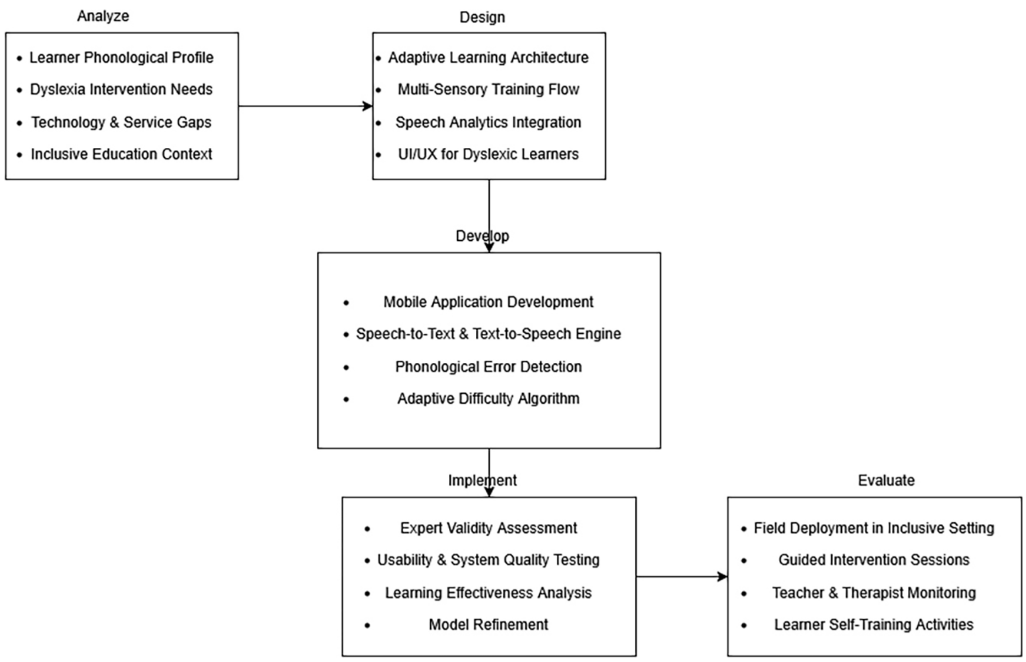

Fig. 2. ADDIE model mind map

Data collection in this study was designed to comprehensively capture both learning outcomes and system quality of the proposed mobile adaptive multi-sensory AI intervention. To achieve this objective, the study employed a mixed-methods data collection strategy, integrating quantitative performance measures with qualitative evaluative data. Quantitative data were collected to measure changes in learners' phonological reading abilities before and after the intervention, as well as to evaluate system performance and usability. These data provide objective evidence of intervention effectiveness and technical feasibility. Qualitative data were collected to complement quantitative findings by capturing expert judgements, user experiences, and contextual insights related to system implementation in inclusive education settings. Data collection was conducted during three main phases: pre-intervention (baseline assessment), intervention implementation, and post-intervention evaluation [25].

Data collection. Data collection in this study employed a mixed-methods approach to capture both learning outcomes and system quality of the adaptive multi-sensory AI intervention. Quantitative data were obtained through phonological reading assessments and speech analytics metrics, including phoneme accuracy, phoneme error rate (PER), word error rate (WER), and articulation duration. These measurements were collected during pre-intervention and post-intervention phases to evaluate improvements in learners' phonological performance.

In addition, system-related data were collected through expert validation instruments and usability questionnaires. Expert validation involved specialists in educational technology, speech processing, and inclusive education, while usability data were gathered from learners and therapists using Likert-scale questionnaires. Observational data were also collected to support quantitative findings [26]. The instruments and indicators used for data collection, including learning outcomes, system quality, and expert validation measures, are detailed in Table 3.

Table 3. Instrument indicators for data collection

Aspect	Indicator	Measurement Method
Learning Outcomes	Phoneme accuracy, PER, WER	Speech analytics and reading tests
Learning Outcomes	Reading fluency	Syllables per minute
System Quality	Functional suitability	Black-box testing
System Quality	Usability	Likert-scale questionnaire
Expert Validation	Content & technical validity	Expert judgement

Data analysis. Data analysis was conducted using descriptive and inferential statistical techniques. Functional suitability was calculated using a Guttman scale to determine the proportion of successfully implemented system features. Expert validity was analysed using Aiken's V coefficient, while usability was assessed using percentage-based Likert-scale analysis.

- Functional Suitability Index: $\mathbf{X = PI}$
- Aiken's V for expert validity: $\mathbf{V = \Sigma s/[n(c - 1)]}$
- Usability Percentage: Usability (%) = **(Obtained Score/Maximum Score) × 100%**
- Learning effectiveness was evaluated by comparing pretest and posttest scores using a paired-sample t-test at a significance level of 0.05. Speech analytics performance was further analysed using PER and WER metrics. PER/WER formula: $\mathbf{PER = (S + D + I)/N}$

3 RESULT AND DISCUSSION

3.1 System feasibility and validity

System feasibility and validity evaluation were conducted to ensure that the developed mobile adaptive multi-sensory AI intervention met predefined functional, technical, and pedagogical requirements prior to effectiveness testing. This evaluation stage is critical in research and development–based studies, as it verifies whether the system operates as intended and is suitable for implementation in real educational settings.

Figure 3 presents the application interface outputs of the Baca Lexia mobile system, illustrating the progression of phonological training from single-syllable to two-syllable and three-syllable reading tasks. These interface outputs demonstrate how the proposed adaptive multi-sensory AI system operationalises phonological dyslexia intervention through structured task sequencing, auditory reinforcement, and learner interaction. The interface design reflects a gradual increase in phonological complexity, which is essential for learners with phonological dyslexia, who typically experience difficulties when processing multi-syllabic words.

Fig. 3. Application interface results for phonological training

The application interface results confirm that the developed system successfully implements a progressive phonological training structure, moving from simple to more complex syllabic forms. The consistent placement of the audio playback feature across all training levels ensures continuity of auditory reinforcement, which is critical for learners with phonological dyslexia. The visual consistency across interfaces minimises extraneous cognitive load, allowing learners to focus on phonological processing rather than interface navigation. Additionally, the clear segmentation of syllables and the use of familiar imagery support phonological awareness and pronunciation accuracy. Overall, the interface outputs demonstrate that the system is not only functionally operational but also pedagogically aligned with dyslexia intervention strategies. These visual results provide concrete evidence that the adaptive multi-sensory AI model has been effectively translated into a practical mobile learning application, complementing the quantitative findings on usability, learning effectiveness, and speech analytics performance reported in previous sections.

Feasibility assessment focused on functional suitability, examining whether all core system features such as speech analytics, adaptive difficulty adjustment, and multi-sensory interaction were successfully implemented and operated without critical errors. Validity assessment was conducted through expert judgement, involving specialists in educational technology, speech and language processing, and inclusive education. Expert validation aimed to determine the appropriateness, accuracy, and relevance of the system from both technical and pedagogical perspectives shown in Table 4. The results of expert validation assessing the educational, technical, and inclusive design aspects of the adaptive multi-sensory AI system are presented in Table 4.

Table 4. Expert validity results of the adaptive multi-sensory AI system

Validator Domain	Number of Items	Aiken's V	Validity Category
Educational Technology Expert	12	0.89	High validity
Speech and Language Expert	10	0.87	High validity
Inclusive Education Expert	10	0.90	High validity
Overall Validity	32	0.887	High validity

The expert validity results indicate that the developed system achieved a high level of validity across all expert domains, with Aiken's V values exceeding the commonly accepted threshold of 0.80. The highest validity score was obtained from the inclusive education expert, indicating strong alignment with the characteristics and needs of learners with phonological dyslexia.

Validation by speech and language experts confirms that the speech analytics and phonological feedback mechanisms embedded in the system are appropriate for phonological rehabilitation. Functional feasibility testing further showed that all designed system features operated successfully, resulting in a functional suitability index of 100%.

3.2 Usability results

Usability evaluation was conducted to examine the extent to which the developed mobile adaptive multi-sensory AI system is easy to use, understandable, and acceptable for its intended users. In the context of dyslexia intervention, usability plays a critical role, as learners with phonological dyslexia may experience cognitive overload when interacting with complex digital interfaces. The usability assessment involved both learners and therapists. Data were collected using a Likert-scale questionnaire covering key usability dimensions, including ease of use, interface clarity, learnability, and user satisfaction. The usability evaluation results of the adaptive AI-based dyslexia intervention, covering ease of use, interface clarity, learnability, and user satisfaction, are presented in Table 5.

Table 5. Usability evaluation results of the adaptive AI-based dyslexia intervention

Usability Aspect	Mean Score (%)	Interpretation
Ease of Use	86.5	Very feasible
Interface Clarity	88.0	Very feasible
Learnability	84.2	Very feasible
User Satisfaction	89.1	Very feasible
Overall Usability	86.9	Very feasible

The usability results indicate that the system achieved a very feasible level across all assessed aspects, with an overall usability score of 86.9%. High scores in ease of use and interface clarity suggest that the system interface is intuitive and accessible for learners with phonological dyslexia. The high user satisfaction score further reflects positive acceptance by both learners and therapists. Overall, these findings demonstrate that the system provides a user-centred learning environment and is suitable for practical implementation in inclusive education settings.

3.3 Learning effectiveness results

Learning effectiveness evaluation was conducted to examine the impact of the mobile adaptive multi-sensory AI intervention on learners' phonological reading performance. Effectiveness was measured by comparing learners' performance before (pre-test) and after (post-test) the intervention period using a pre- and post-test control group design.

The experimental group received the adaptive AI-based intervention, while the control group followed conventional phonological reading activities. This comparison allows the analysis to identify differences in learning improvement attributable to the proposed system. The comparison of pretest and posttest phonological reading performance between the experimental and control groups is presented in Table 6.

Table 6. Pre- and post-test results of phonological reading performance

Group	Test	Mean Score	Standard Deviation
Experimental	Pre-test	62.4	6.8
Experimental	Post-test	82.7	5.9
Control	Pre-test	63.1	7.1
Control	Post-test	69.3	6.5

The results show a substantial improvement in phonological reading performance for learners in the experimental group after participating in the adaptive AI-based intervention. The mean score increased from 62.4 in the pre-test to 82.7 in the post-test, indicating a notable gain in phonological accuracy and reading ability. In contrast, the control group demonstrated only a modest improvement, with mean scores increasing from 63.1 to 69.3. This difference in score progression suggests that learners who engaged with the mobile adaptive AI system benefited more than those who received conventional instruction alone. The comparison between experimental and control groups indicates that the proposed intervention contributed positively to learning outcomes. These findings provide initial empirical evidence supporting the effectiveness of adaptive multi-sensory AI-based intervention for improving phonological reading skills in learners with dyslexia. Statistical significance testing is presented in the subsequent analysis section to further substantiate these results.

3.4 Learning effectiveness results

Speech analytics performance evaluation was conducted to objectively examine changes in learners' phonological accuracy during the intervention. This evaluation employed PER and WER metrics derived from learners' speech data collected during pre-intervention and post-intervention sessions. These metrics provide detailed measurements of pronunciation errors, including substitution, deletion, and insertion errors, which are characteristic of phonological dyslexia. The use of speech analytics allows a more precise assessment of phonological rehabilitation outcomes compared to conventional reading tests alone. The changes in speech analytics performance, measured using PER and WER before and after the intervention, are presented in Table 7.

Table 7. Speech analytics performance before and after intervention

Group	Metric	Pretest Mean	Posttest Mean
Experimental	PER	0.38	0.16
Experimental	WER	0.42	0.18
Control	PER	0.37	0.31
Control	WER	0.41	0.34

The results show a marked reduction in phonological errors among learners in the experimental group following the adaptive AI-based intervention. PER decreased from 0.38 to 0.16, and WER decreased from 0.42 to 0.18, indicating substantial improvements in phoneme-level and word-level pronunciation accuracy. In contrast, the control group demonstrated only minor reductions in error rates. These findings suggest that the adaptive multi-sensory AI system contributed to more effective phonological rehabilitation compared to conventional instruction.

4 DISCUSSION

The findings of this study demonstrate that the proposed mobile adaptive multi-sensory AI model with real-time speech analytics constitutes an effective and feasible approach for phonological dyslexia intervention. The combination of high system feasibility and validity, strong usability ratings, significant learning gains, and objective reductions in phonological error rates indicates that the intervention successfully addresses both technical implementation requirements and pedagogical needs of learners with phonological dyslexia. The high expert validity scores suggest that the system design aligns well with principles of inclusive education, phonological rehabilitation, and educational technology. From a pedagogical perspective, experts recognised that the structured progression from single-syllable to multi-syllable tasks reflects evidence-based dyslexia intervention strategies, which emphasise gradual scaffolding and repetition. Technically, the validation results confirm that the integration of speech analytics and adaptive mechanisms functions reliably within a mobile environment, supporting the system's readiness for real-world implementation. Usability results further reinforce the practicality of the proposed system. High scores in ease of use, interface clarity, and user satisfaction indicate that learners were able to interact with the application without excessive cognitive burden. This finding is particularly important for learners with phonological dyslexia, who are often sensitive to complex interfaces and cognitively demanding tasks. The consistent layout, clear visual cues, and accessible audio controls observed in the application interface outputs contribute to reduced extraneous cognitive load, allowing learners to focus on phonological processing rather than navigation or interface comprehension.

Overall, the findings suggest that integrating adaptive learning logic, multi-sensory stimulation, and speech analytics within a mobile platform offers a promising solution for scalable and inclusive dyslexia intervention. While the study demonstrates encouraging results, it is important to acknowledge that the sample size was limited and the intervention duration relatively short. Future research should involve larger and more diverse participant groups, longer intervention periods, and advanced speech analysis techniques to further validate and extend the applicability of the proposed model.

5 CONCLUSION

This study demonstrates that a mobile adaptive multi-sensory AI model integrated with real-time speech analytics can serve as an effective, feasible, and user-friendly solution for phonological dyslexia intervention. The integration of adaptive learning mechanisms, multi-sensory stimulation, and objective speech analytics enables the system to respond dynamically to individual learner needs, addressing one of the core limitations of conventional, non-adaptive dyslexia interventions. Despite these promising outcomes, this study has several limitations. The sample size was relatively small, and the intervention was conducted over a limited duration. Future research should involve larger participant populations, extended intervention periods, and more advanced speech analytics techniques, such as deep phoneme classification and affect-aware feedback mechanisms. Additionally, longitudinal studies are needed to examine the sustainability of learning gains over time.

In conclusion, this study contributes to the growing body of research on AI-assisted inclusive education by providing empirical evidence that adaptive, multi-sensory, and speech-driven mobile interventions can effectively support phonological dyslexia rehabilitation. The proposed model offers a practical foundation for developing scalable and data-driven dyslexia intervention tools that bridge technological innovation and educational inclusion.

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8 AUTHORS

Resmi Darni is a professional educator, futurologist, dedicated researcher, technology consultant at Truverse, a company engaged in the development of AI-based technologies, and Assistant Professor at the Faculty of Engineering, Indonesia, specialising in Information and Computer Engineering Education, Universitas Negeri Padang (UNP) (E-mail: resmidarni@ft.unp.ac.id).

Yulyanti Harisman is a professional educator, highly dedicated researcher, and assistant professor at the Faculty of Natural Sciences, Universitas Negeri Padang (UNP), Indonesia, specialising in mathematics education. Yuliyanti Harisma is also a reviewer for national and international journals such as Jurnal Euclid, Journal of Honaymath, Jurnal Penelitian Pembelajaran Matematika di Sekolah, and Journal of Authentic Research on Mathematics Education (E-mail: yulyanti_h@fmipa.unp.ac.id).

Lili Dasa Putri is a professional educator, dedicated researcher, and assistant professor at the Faculty of Education, Universitas Negeri Padang (UNP), Indonesia. She currently serves as a lecturer in the Department of Nonformal Education, specialising in community education strategies and instructional development. With a strong commitment to academic excellence and social empowerment, her work focuses on bridging the gap between theoretical pedagogy and practical community-based learning (E-mail: lilidasaputri@fip.unp.ac.id).

Efi Fitriana is a professional educator, highly dedicated researcher, and assistant professor at the Faculty of Psychology, specialising in statistics and quantitative measurement, at Universitas Padjadjaran, Bandung, Indonesia. Efi Fitriana is also a test and psychometric consultant who has developed the Knowledge, Attitudes, and Behaviour of Community Pharmacy Personnel in Tuberculosis (TB) Patient Management test instrument and the Family Relations-Bandung test instrument (E-mail: efi.fitriana@unpad.ac.id).

Rezki Ashriyana Sulistiobudi is a researcher specialising in industrial-organisational psychology at Universitas Padjadjaran, Bandung, Indonesia. Rezki is also a psychologist, handling various consulting and human resource development projects in organisations. His research expertise focuses on employability and work behaviour within organisations. As a relatively young academic, Rezki has produced many productive works, including 12 high-impact international journals, numerous reputable national journals, 7 books, and 26 intellectual property rights. Rezki has also contributed to various partnership collaborations and community service projects between the Faculty of Psychology at Universitas Padjadjaran and various government and private institutions. Most of these collaborations involve the development of assessment instruments for human resource potential and competency, including with the Ministry of Finance, the Ministry of Education and Culture, and the National Civil Service Agency (BKN). His insights have been utilised for the development of CASN and P3K selection instruments in Indonesia with the Educational Assessment Center. Additionally, the results of his collaboration with BKN have been used for mapping the competencies of civil servants across Indonesia (E-mail: rezki.ashriyana@unpad.ac.id).

Andhika Herayono is a Doctoral student and researcher at the Department of Informatics Engineering Education, Faculty of Engineering, Universitas Negeri Padang, Indonesia. His research interests focus on artificial intelligence in education, adaptive learning systems, educational data analytics, gamification, and technology-enhanced learning in vocational and inclusive education contexts. He has authored and co-authored several publications indexed in Scopus, particularly in the areas of mobile learning, AI-assisted instruction, and digital learning innovation (E-mail: andhikaherayono99@gmail.com).