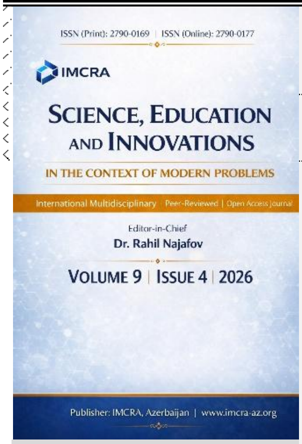

Science, Education and Innovations in the Context of Modern Problems
Issue 5, Vol. 9, 2026

RESEARCH ARTICLE

DGPA and Smart Phono-Memory: A Novel Theoretical Framework and Adaptive Digital Tool for Arabic Reading

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Keywords
Arabic dyslexia; phonological awareness; working memory; diacritic processing; adaptive digital intervention; Smart Phono-Memory (SPM); Diacritic-Gated Phonological Access (DGPA)

Abstract
Developmental dyslexia in Arabic-speaking children presents unique challenges due to the structural and orthographic characteristics of the Arabic language, particularly the role of vowel diacritics in phonological decoding. Existing intervention models, primarily designed for Indo-European languages, often do not adequately account for these language-specific features. This study introduces *Smart Phono-Memory (SPM)*, an adaptive digital tool designed to support phonological processing through the integration of phonological awareness training, working memory activation, and controlled manipulation of vowelized and non-vowelized stimuli. In parallel, the study proposes the *Diacritic-Gated Phonological Access (DGPA)* model, which reconceptualizes diacritic processing as a central regulatory mechanism in Arabic reading. The proposed framework emphasizes the interaction between orthographic transparency and cognitive processing, highlighting how diacritic cues influence the stability of phonological representations. It further explores the relationship between phonological awareness and working memory as interdependent components in the decoding process. The adaptive nature of the SPM system allows for individualized progression, aligning task complexity with the learner's cognitive profile and reducing processing overload. In addition, the study situates Arabic reading within a broader cognitive-linguistic context, underscoring the importance of language-specific variables in literacy development. The integration of digital technology with theoretical modeling offers a novel perspective on intervention design, bridging the gap between cognitive theory and applied educational practice. The findings contribute to an emerging body of research advocating for culturally and linguistically responsive approaches in dyslexia intervention. By situating phonological processing within a language-specific cognitive framework, this work advances the theoretical understanding of Arabic reading acquisition and highlights the importance of adaptive, linguistically grounded digital interventions for addressing dyslexia in non-European orthographies.

Citation
Sarah, R., Kahina L. (2026). DGPA and Smart Phono-Memory: A Novel Theoretical Framework and Adaptive Digital Tool for Arabic Reading. *Science, Education and Innovations in the Context of Modern Problems, 9*(5), 1–19.
https://doi.org/10.56334/sei/9.5.4

Received: August 15.2025 | **Accepted:** February 15.2026 | **Published Online:** April 10. 2026

Introduction

Developmental dyslexia is a persistent neurodevelopmental disorder affecting approximately 5–10% of school-aged children worldwide and characterized by severe difficulties in accurate and fluent word recognition, spelling, and decoding despite adequate intelligence and adequate educational exposure (Peterson & Pennington, 2012; Snowling, 2000). Converging cognitive and neuropsychological evidence identifies deficits in phonological processing as the principal mechanism underlying reading difficulties in dyslexia (Vellutino et al., 2004).

Phonological awareness—the ability to analyze and manipulate speech sounds—is the strongest predictor of reading acquisition across alphabetic languages (Melby-Lervåg et al., 2012). Children with dyslexia show persistent impairments in phoneme segmentation, blending, and grapheme–phoneme correspondence, leading to unstable orthographic representations and poor decoding skills (Ehri, 2005; Snowling, 2013). These deficits are often compounded by limitations in verbal working memory, particularly in the phonological loop component described by Baddeley's multicomponent model, which supports temporary storage and rehearsal of phonological information (Baddeley, 2000; Gathercole & Alloway, 2008).

Evidence-based structured literacy interventions that explicitly train phonological skills and decoding processes significantly improve reading outcomes (National Reading Panel, 2000; Galuschka et al., 2014). However, working-memory training alone shows limited transfer to academic reading performance when not integrated into literacy instruction (Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017). These findings highlight the importance of integrated therapeutic approaches combining phonological training with cognitive scaffolding.

Recent advances in educational technology have enabled adaptive digital interventions capable of individualized pacing, immediate feedback, and increased learner motivation (Cheung & Slavin, 2013; Benavides-Varela et al., 2020). Yet most existing programs were designed for Indo-European languages and do not adequately account for the orthographic characteristics of Arabic, where vowel diacritics play a central role in phonological decoding.

Research on Arabic literacy shows that diacritics significantly facilitate word recognition and phonological decoding in early reading and in children with dyslexia, because they make phoneme–grapheme correspondences more transparent (Abu-Rabia & Taha, 2006; Taha & Saiegh-Haddad, 2017). Studies also demonstrate that removing diacritics increases cognitive load and working-memory demands during reading in Arabic (Saiegh-Haddad & Geva, 2008). These findings suggest that controlled manipulation of vowelization can serve as a therapeutic tool to strengthen phonological representations and decoding pathways.

Despite this evidence, few digital therapeutic programs have systematically integrated Arabic diacritics into adaptive phonological training combined with working-memory stimulation. Addressing this gap, the present study introduces Smart Phono-Memory (SPM), an adaptive digital therapeutic platform developed in Python for Arabic-speaking children with phonological dyslexia. The program integrates evidence-based phonological training with intelligent adaptive algorithms and interactive manipulation of vowelized and non-vowelized stimuli, aiming to reinforce grapheme–phoneme mapping while activating the phonological loop in working memory.

By combining structured literacy principles with Arabic-specific orthographic features and adaptive digital learning, SPM seeks to provide a culturally and linguistically appropriate intervention model capable of enhancing phonological awareness, working memory, and decoding skills in children with dyslexia.

Beyond its functional utility as a digital intervention, Smart Phono-Memory (SPM) serves as the empirical embodiment of a novel theoretical framework. This study moves from software implementation to theoretical conceptualization by proposing the Diacritic-Gated Phonological Access (DGPA) model. Within this framework, diacritic processing is redefined not as an auxiliary orthographic feature, but as a mandatory regulatory mechanism that gates phonological retrieval and stabilizes the grapheme-to-phoneme mapping in Arabic. Consequently, SPM acts as the clinical laboratory through which the DGPA model is validated, offering a paradigm shift from generic phonological training to a language-specific cognitive architecture tailored for the Arabic-speaking dyslexic brain.

Research Problem

Despite significant advances in evidence-based dyslexia interventions, many therapeutic programs remain insufficiently adapted to the linguistic characteristics of non-European orthographies. Most digital tools are designed for English or similar alphabetic systems and rarely account for the role of vowel diacritics in Arabic, which directly influence phonological decoding and reading accuracy (Abu-Rabia & Taha, 2006; Saiegh-Haddad & Geva, 2008). Consequently, Arabic-speaking children with phonological dyslexia often receive interventions that do not adequately address the specific interaction between phonological awareness, working memory, and orthographic transparency.

In addition, although phonological awareness training is widely recognized as effective, its impact is reduced when working-memory deficits are not simultaneously addressed (Swanson & Siegel, 2001; Melby-Lervåg & Hulme, 2013). Digital cognitive-training programs exist, but few integrate adaptive phonological exercises with controlled manipulation of vowelization to support grapheme–phoneme mapping in Arabic. This gap highlights the need for a scientifically grounded therapeutic platform capable of combining structured phonological training, working-memory activation, and Arabic-specific orthographic features within an adaptive digital environment.

Research Objectives

The present study aims to design and evaluate Smart Phono-Memory (SPM), an adaptive digital therapeutic program developed in Python to support Arabic-speaking children with phonological dyslexia. The first objective is to create a structured training environment that simultaneously stimulates phonological awareness and the phonological loop component of working memory through progressive and adaptive exercises.

A second objective is to examine the therapeutic value of interactive manipulation of Arabic diacritics within the program. By presenting letters, syllables, and words in both vowelized and non-vowelized forms, SPM seeks to reinforce grapheme–phoneme correspondences and facilitate decoding processes specific to Arabic orthography.

A third objective is to evaluate the procedural feasibility and motivational impact of the program during an exploratory pilot phase involving two clinical cases. This phase focuses on verifying the technical efficiency of the algorithm, the usability of the interface, and the qualitative therapeutic effects compared with traditional intervention approaches that were previously rejected by the children.

Research Questions

This study addresses the following research questions. First, can an adaptive digital therapeutic program such as Smart Phono-Memory effectively stimulate phonological awareness and working memory in Arabic-speaking children with phonological dyslexia? Second, does interactive manipulation of diacritics within digital stimuli improve phonological decoding and stability of phonological representations? Third, can a gamified and adaptive digital environment increase motivation and engagement compared with traditional therapy approaches?

Hypotheses

It is hypothesized that children using the Smart Phono-Memory program will show qualitative improvements in phonological awareness tasks and increased phonological working-memory span after the intervention period. It is also expected that vowelized stimuli will facilitate decoding accuracy more effectively than non-vowelized stimuli, particularly for children with deficits in phonological awareness. Finally, it is anticipated that the adaptive and gamified structure of SPM will enhance engagement and reduce avoidance behaviors observed in traditional therapy contexts.

Theoretical Framework

Literature Review

Cognitive and Neuropsychological Foundations of Developmental Dyslexia

Developmental dyslexia is conceptualized as a neurodevelopmental disorder primarily rooted in deficits in phonological processing rather than general intellectual impairment (Peterson & Pennington, 2012; Snowling, 2000). Longitudinal and experimental research has consistently demonstrated that difficulties in representing, accessing, and manipulating phonological units of language constitute the core cognitive marker of dyslexia (Vellutino et al., 2004). These phonological deficits compromise the establishment of stable grapheme–phoneme correspondences, leading to inaccurate decoding and reduced reading fluency.

Neurobiological investigations further support this perspective. Functional neuroimaging studies reveal underactivation in left temporo-parietal regions associated with phonological decoding and mapping processes in individuals with dyslexia (Shaywitz & Shaywitz, 2008; Dehaene, 2009). These findings align with the phonological deficit hypothesis, suggesting that reading difficulties emerge from inefficient neural processing within networks responsible for phonological analysis and orthographic integration.

Importantly, dyslexia is increasingly understood as a heterogeneous condition, with variability in cognitive profiles. Some children exhibit predominant phonological awareness deficits, while others show additional impairments in rapid naming or verbal working memory (Pennington, 2006). This variability underscores the need for adaptive interventions tailored to specific cognitive profiles rather than uniform remediation programs.

Phonological Awareness and Reading Acquisition

Phonological awareness—the ability to consciously manipulate speech sounds—has been identified as one of the strongest predictors of reading acquisition across alphabetic orthographies (Melby-Lervåg et al., 2012). Skills such as phoneme segmentation, blending, deletion, and substitution are foundational for decoding unfamiliar words and developing orthographic representations (Ehri, 2005).

Ehri's phase theory of word reading development posits that children progress from pre-alphabetic to full alphabetic and consolidated alphabetic phases, during which grapheme–phoneme mapping becomes increasingly automated. Children with dyslexia often remain delayed in these phases due to unstable phonological representations (Ehri, 2005; Snowling, 2013).

Meta-analyses confirm that explicit and systematic phonics instruction significantly improves decoding skills, especially when combined with phoneme-awareness training (National Reading Panel, 2000; Galuschka et al., 2014). Structured literacy approaches emphasize cumulative, explicit instruction in sound–symbol relationships and have demonstrated robust evidence of effectiveness for learners with dyslexia (International Dyslexia Association, 2019).

However, phonological awareness alone does not fully explain reading performance. The efficiency with which phonological information is temporarily stored and manipulated also plays a crucial role, particularly when decoding multisyllabic words or maintaining sequences of phonemes.

Working Memory and the Phonological Loop

Baddeley's multicomponent model of working memory proposes a phonological loop responsible for short-term storage and rehearsal of verbal material (Baddeley, 2000). This subsystem supports the temporary maintenance of phonological information necessary for decoding, spelling, and sentence comprehension.

Research indicates that children with dyslexia frequently exhibit reduced phonological short-term memory span, which correlates with reading accuracy and spelling performance (Swanson & Siegel, 2001). Working memory limitations increase cognitive load during decoding, particularly when grapheme–phoneme correspondences are not automatized.

Despite theoretical links between working memory and reading, interventions focused solely on working-memory training have shown limited far-transfer effects to academic performance (Melby-Lervåg & Hulme, 2013; Sala & Gobet, 2017). Improvements often remain task-specific unless training is integrated within literacy-focused activities. These findings suggest that working memory should be stimulated within meaningful phonological contexts rather than through isolated cognitive drills.

Consequently, integrated interventions that simultaneously engage phonological awareness and phonological memory may offer greater ecological validity and stronger transfer to reading outcomes.

Orthographic Transparency and the Role of Diacritics in Arabic Reading

Arabic orthography presents distinctive characteristics that influence reading acquisition. While the consonantal script provides morphological cues, short vowels are typically represented through diacritics that clarify phonological information. When diacritics are present, orthographic transparency increases; when absent, readers must rely more heavily on lexical and contextual knowledge (Abu-Rabia & Taha, 2006).

Empirical studies demonstrate that vowelized text significantly improves decoding accuracy among beginning readers and children with dyslexia (Saiegh-Haddad & Geva, 2008). Diacritics facilitate grapheme–phoneme correspondence by making phonological information explicit, thereby reducing ambiguity during word recognition. Conversely, the absence of diacritics increases reliance on working memory and lexical retrieval processes.

Research also indicates that children with phonological dyslexia benefit from structured exposure to vowelized stimuli, as this strengthens phonemic representations and supports decoding fluency (Taha & Saiegh-Haddad, 2017). Importantly, diacritics can serve as a scaffold for phonological processing rather than merely an orthographic feature.

However, few digital interventions have systematically incorporated controlled manipulation of diacritics as a therapeutic variable. Most programs treat vowelization as a static feature rather than an adaptive tool capable of modulating task difficulty and cognitive load.

Digital and Adaptive Interventions in Dyslexia

Advances in educational technology have introduced computer-assisted interventions designed to enhance motivation, provide immediate feedback, and individualize pacing (Cheung & Slavin, 2013). Digital environments can increase engagement, particularly for children who exhibit resistance to traditional therapy formats.

Studies investigating technology-based interventions for reading disorders show moderate improvements in phonological processing and decoding accuracy (Benavides-Varela et al., 2020). Gamification elements, adaptive difficulty progression, and performance analytics contribute to sustained attention and practice intensity.

Neuroplasticity research suggests that repeated, targeted practice can strengthen neural circuits associated with reading (Shaywitz & Shaywitz, 2008). Digital platforms allow high-frequency repetition within structured frameworks aligned with evidence-based literacy principles.

Nevertheless, challenges remain. Many digital programs lack linguistic specificity, are not grounded in robust cognitive theory, or fail to integrate phonological training with working-memory activation. Additionally, empirical evidence regarding long-term generalization to classroom reading performance remains mixed (Hall et al., 2016).

While digital advancements offer promising avenues for dyslexia remediation, most existing platforms lack the linguistic specificity required for the Arabic orthographic context. There is an urgent need for a framework that transcends simple gamification by embedding language-specific variables into the core of the adaptive therapeutic training process. This necessity provides the scientific rationale for Smart Phono-Memory (SPM), conceptualized as an integrated therapeutic architecture designed to address the unique cognitive-linguistic profile of Arabic-speaking children with dyslexia.

The Rationale for Smart Phono-Memory (SPM)

The literature converges on three central principles: (1) phonological deficits are foundational in dyslexia; (2) working memory contributes to decoding efficiency; (3) Arabic diacritics significantly influence phonological transparency.

However, an integrated therapeutic model combining these elements within an adaptive digital environment remains underexplored. Smart Phono-Memory (SPM) was therefore conceptualized to bridge this gap. The program integrates structured phonological awareness exercises with activation of the phonological loop and dynamic manipulation of vowelized and non-vowelized stimuli. By adjusting task complexity according to user performance, SPM seeks to optimize cognitive load while reinforcing grapheme–phoneme mapping.

Grounded in cognitive theory, orthographic research, and principles of adaptive learning, SPM aims to offer a culturally and linguistically appropriate therapeutic framework for Arabic-speaking children with phonological dyslexia. The present exploratory study constitutes the initial developmental phase of this model.

Conceptual Model of Smart Phono-Memory (SPM)

The conceptual framework of Smart Phono-Memory (SPM) is grounded in cognitive models of developmental dyslexia that identify phonological processing deficits and limitations in verbal working memory as primary mechanisms underlying reading difficulties (Vellutino et al., 2004; Baddeley, 2000). The model assumes that effective remediation must simultaneously stimulate phonological awareness and the phonological loop while adapting task difficulty to the child's cognitive profile.

Within this framework, SPM is conceptualized as an adaptive therapeutic system integrating three core components: structured phonological training, working-memory activation, and controlled manipulation of Arabic diacritics. These components interact dynamically to reinforce grapheme–phoneme correspondences and stabilize phonological representations.

First, phonological-awareness exercises (segmentation, blending, and phoneme manipulation) aim to strengthen the accuracy of phonological representations, which are essential for decoding processes (Ehri, 2005). Second, timed stimulus presentation and recall tasks activate the phonological loop, enhancing temporary storage and rehearsal capacity in working memory (Gathercole & Alloway, 2008). Third, the interactive manipulation of vowelized and non-vowelized stimuli increases orthographic transparency and supports phoneme–grapheme mapping in Arabic reading (Abu-Rabia & Taha, 2006).

The adaptive algorithm serves as a mediating mechanism that adjusts task complexity according to the child's response patterns. By maintaining tasks within the "zone of optimal challenge," the program reduces frustration while maximizing cognitive engagement. Gamified feedback acts as a motivational moderator that enhances sustained attention and participation in therapy.

The expected outcome of this interaction is improved phonological awareness, increased phonological working-memory span, enhanced decoding accuracy, and greater motivation toward reading activities. These proximal gains are hypothesized to contribute to improved reading fluency and orthographic learning over time.

SEM Framework of SPM

The conceptual framework of Smart Phono-Memory (SPM) can be formalized as a structural equation model (SEM) in which the program exerts its effect on reading outcomes through mediating cognitive variables and moderated by motivational factors. The model integrates theoretical insights from phonological deficit theories, working-memory models, and Arabic orthographic research.

Variables of the SEM

Independent Variable (IV): SPM Intervention — the adaptive digital therapeutic program combining phonological training, working-memory activation, and interactive manipulation of Arabic diacritics.

Mediating Variables (MV): (1) Phonological Awareness: measured by tasks of phoneme segmentation, blending, and manipulation. (2) Phonological Working Memory: measured by span tasks, including recall of letters, syllables, and short words presented in timed conditions.

Moderator Variable (ModV): Motivation/Engagement: operationalized as participation rates, time on task, and response to gamified feedback.

Dependent Variables (DV): (1) Decoding Accuracy: accuracy in reading vowelized and non-vowelized Arabic words and pseudo-words. (2) Phonological Representation Stability: operationalized as consistent correct recall across trials.

Hypothesized Paths

- SPM → Phonological Awareness: Structured phonological exercises directly improve awareness (Ehri, 2005; Melby-Lervåg et al., 2012).
- SPM → Working Memory: Timed exposure and recall tasks activate and strengthen the phonological loop (Baddeley, 2000; Swanson & Siegel, 2001).
- Phonological Awareness → Decoding Accuracy: Stronger phonological awareness predicts more accurate grapheme–phoneme mapping (Snowling, 2013).
- Working Memory → Decoding Accuracy: Higher span allows maintenance of phonological sequences during reading (Gathercole & Alloway, 2008).
- Motivation → Phonological Awareness & Working Memory: Motivation moderates the effectiveness of training through sustained attention and engagement (Benavides-Varela et al., 2020).
- Decoding Accuracy → Phonological Representation Stability: Accurate decoding reinforces stable mental representations of phonemes and words.
- Indirect Paths: SPM impacts reading outcomes indirectly via both mediators, with moderation by motivation.

Figure 1. Structural Equation Model (SEM) of the Smart Phono-Memory (SPM) intervention. The model illustrates direct effects of the adaptive digital program on phonological awareness and working memory, with motivation as a moderating variable, and indirect effects on decoding accuracy and phonological representation stability. IV: Intervention (SPM); MV: Mediators (Phonological Awareness, Working Memory); ModV: Motivation; DV: Reading outcomes (Decoding Accuracy, Phonological Stability).

Rationale for SEM

The SEM approach allows testing direct, indirect, and moderated effects of the SPM program. It quantifies how much phonological awareness and working memory mediate the impact of digital training on reading performance. It includes motivation as a moderator, reflecting real-world engagement differences. It aligns the theoretical model with empirical testing, supporting causal inferences even in pilot studies.

This framework sets the stage for future larger-sample studies and potential multigroup SEM analysis (e.g., comparing vowelized vs. non-vowelized stimuli) to quantify the contribution of linguistic features in Arabic reading development.

Methodology

Research Design

This study adopts an exploratory developmental research design, combining elements of case study analysis and design-based research (DBR). The primary objective is to develop, implement, and preliminarily evaluate the effectiveness of an adaptive digital therapeutic system—Smart Phono-Memory (SPM)—for Arabic-speaking children with phonological dyslexia.

Given the innovative nature of the intervention and the focus on system feasibility, usability, and initial cognitive outcomes, a pilot study framework was employed. This approach enables in-depth observation of individual cognitive processes while generating preliminary empirical evidence to inform future large-scale experimental research.

Participants

The study involved two children diagnosed with phonological dyslexia, selected through purposive sampling. Inclusion criteria were as follows:

- Clinical diagnosis of phonological dyslexia confirmed through standardized assessments
- Age range between 9 and 11 years
- Average intellectual functioning (as measured by Raven's Progressive Matrices)

- Absence of neurological disorders, sensory impairments, or intellectual disability

Participant Profiles

- Participant A (A.W.): 9 years 8 months; primary deficit in phonological working memory (limited span capacity)
- Participant B (R.L.): 10 years 6 months; primary deficit in phonological awareness, particularly in diacritic processing

Both participants had previously demonstrated low engagement with traditional intervention methods, making them suitable candidates for testing a digital, adaptive, and gamified therapeutic approach.

Ethical Considerations

The study adhered to established ethical standards for research involving human participants.

- Informed consent was obtained from parents/legal guardians
- Participants' identities were anonymized using coded identifiers
- The study complied with principles outlined in the Declaration of Helsinki
- Participation was voluntary, with the right to withdraw at any stage

Intervention Tool: Smart Phono-Memory (SPM)

Smart Phono-Memory (SPM) is a Python-based adaptive digital intervention system designed to simultaneously stimulate phonological awareness and activate the phonological loop in working memory.

Core Components:

1. Adaptive Algorithm
   Dynamically adjusts task difficulty based on real-time performance
2. Phonological Training Modules
   - Phoneme segmentation
   - Blending tasks
   - Phoneme manipulation exercises
3. Working Memory Activation
   - Timed stimulus presentation
   - Recall tasks requiring phonological retention
4. Diacritic Manipulation System
   - Presentation of stimuli in both vowelized and non-vowelized forms
   - Gradual increase in orthographic complexity
5. Gamification Features
   - Immediate feedback
   - Reward-based motivation (points, badges)
6. User Interface
   Developed using Python (Tkinter), ensuring accessibility and child-friendly interaction

Procedure

1. Baseline Assessment

Participants underwent pre-intervention evaluation using standardized and observational measures:

- Reading accuracy tests (vowelized and non-vowelized Arabic words)
- Phonological awareness tasks (segmentation, blending, manipulation)
- Working memory span tasks (letters, digits, and words)
- Cognitive assessment using Raven's Progressive Matrices

Behavioral observations (attention, motivation, anxiety) were also recorded.

2. Familiarization Phase

Participants were introduced to the SPM system through guided interaction sessions, including:

- Explanation of task objectives
- Demonstration of interface functionality
- Practice exercises to ensure operational understanding

3. Intervention Phase

Participants engaged in multiple individualized sessions using SPM. Each session followed a structured protocol:

- Presentation of stimuli (letters, syllables, words) for a controlled duration
- Automatic concealment of stimuli to activate phonological recall
- Immediate feedback provided after each response
- Adaptive adjustment of task complexity based on accuracy

Tasks progressed from simple phonological units (letters) to more complex structures (multi-syllabic words).
4. Data Collection
Data were collected using a mixed-method approach:
Quantitative Data:

- Accuracy rates (% correct responses)
- Reaction time (automatically logged)
- Performance progression across difficulty levels

Qualitative Data:

- Behavioral observations (engagement, persistence, frustration)
- Interaction patterns with the digital system

All quantitative data were recorded automatically through embedded Python logging functions.
5. Post-Intervention Assessment
Following the intervention phase, participants were reassessed using the same instruments as in the baseline phase to evaluate:

- Changes in phonological awareness
- Improvement in working memory span
- Gains in reading accuracy

Data Analysis
Given the exploratory nature and small sample size, analysis focused on descriptive and clinical significance measures:

- Descriptive statistics (pre–post comparison of accuracy scores)
- Effect size (Cohen's d) to estimate magnitude of change
- Reliable Change Index (RCI) to assess clinical significance

Qualitative observations were analyzed thematically to identify patterns in cognitive engagement, error types, and adaptive learning behavior.
Methodological Limitations
This study is subject to several limitations:

- Small sample size ($n = 2$), limiting generalizability
- Absence of a control group
- Short intervention duration
- Exploratory design without randomized assignment

Despite these limitations, the study provides valuable preliminary evidence regarding the feasibility and potential effectiveness of adaptive digital interventions tailored to Arabic orthographic features.

Materials: Smart Phono-Memory (SPM)

Smart Phono-Memory (SPM) is a Python-based adaptive digital program designed to stimulate phonological awareness and activate the phonological loop in working memory through interactive exercises. Key program components include:

- Adaptive algorithm: analyzes the child's responses and dynamically adjusts the difficulty of letters, syllables, and words to maintain an optimal cognitive challenge without causing frustration.
- Interactive diacritics manipulation: presents stimuli in vowelized and non-vowelized forms, supporting grapheme–phoneme mapping in Arabic.
- Phonological exercises: segmentation, blending, and recall tasks to enhance the phonological loop.
- Gamified feedback system: points and virtual badges to motivate participation and sustain attention.
- Graphical user interface: simple, child-friendly interface built using Tkinter, with timed exposure of stimuli and immediate feedback.

Additional materials included standardized assessment tools for phonological awareness, reading accuracy, and working-memory span; record sheets for qualitative observation of engagement and behavioral responses; and Python logging modules to automatically record response accuracy and reaction times.

Procedure

Baseline Assessment

Each participant underwent assessment of phonological awareness, working-memory span, and decoding ability using standardized measures. Observations were recorded on attention, motivation, and reading anxiety levels. General intellectual functioning was assessed using the Raven's Progressive Matrices (RPM). Case 1 (A.W.) obtained a total IQ score of 95, and Case 2 (R.L.) obtained a score of 93, both falling within the average range of intellectual functioning.

These results rule out global intellectual disability and confirm that the observed difficulties are specific rather than attributable to general cognitive impairment.

Program Familiarization

Children were introduced to the SPM interface, including explanations of task goals, buttons, and feedback systems. A brief practice session ensured that participants could navigate the program independently.

Intervention Sessions

Each participant completed multiple individual sessions using the SPM program. During each session:

- Stimuli (letters, syllables, words) were randomly selected and presented for a controlled duration.
- Children were asked to recall and input the correct phonological sequence after stimulus disappearance.
- Immediate positive feedback was provided for correct answers; incorrect answers prompted repetition without negative reinforcement.
- Adaptive adjustments ensured that task difficulty matched the participant's abilities, progressing from simple letters to combinations, syllables, and words.

Observation and Logging

The researcher recorded qualitative data on attention span, engagement, and affective responses. The Python program automatically logged quantitative data including accuracy, response time, and progression through difficulty levels.

Post-Session Assessment

Following the pilot phase, participants were re-evaluated on phonological awareness and working-memory tasks. Comparisons were made with baseline performance to identify procedural effectiveness and preliminary cognitive gains.

Results

Baseline Clinical Assessment

Reading Assessment

The reading assessment revealed distinct phonological decoding profiles in the two cases.

In Case 1 (A.W.), reading was characterized by a letter-by-letter decoding strategy. The child spelled words sequentially, frequently neglecting short vowel diacritics. When attempting to blend the letters into a complete word, he demonstrated difficulty retaining the initial phonemes, leading to repeated re-spelling of the same word. Errors were particularly frequent in short vowel diacritics, resulting in inaccurate word production and semantic distortion.

In Case 2 (R.L.), reading fluency was relatively preserved at the surface level. However, the child consistently neglected long vowel markers, which led to alterations in lexical meaning and loss of contextual coherence. Although decoding speed appeared adequate, phonological precision deficits interfered with semantic integration.

These findings indicate that both cases exhibit phonological decoding disturbances, albeit with different manifestations:

- Case 1: severe phonological assembly deficit
- Case 2: diacritic precision deficit affecting semantic processing

Phonological Awareness

Phonological awareness was evaluated through segmentation, blending, and phoneme manipulation tasks.

Case 1 (A.W.) demonstrated significant impairment across all tasks, including failure in phonemic segmentation, difficulty in phoneme blending, and poor performance in short vowel discrimination. These results suggest an inability to construct stable phonological representations at the sublexical level.

In contrast, Case 2 (R.L.) showed adequate awareness of long vowel markers but displayed inconsistencies in phonological precision when processing diacritic-dependent lexical contrasts.

Overall, the profile of Case 1 reflects a core phonological awareness deficit, whereas Case 2 presents a more selective vulnerability in phonological detail processing.

Working Memory (Phonological Loop)

Working memory was assessed with tasks targeting the phonological loop component.

Case 1 (A.W.): The results revealed a marked structural deficit in short-term phonological storage. Letter span: 2 elements; Number span: 2 elements. This span is significantly below age-related norms and indicates severe limitations in phonological retention capacity. The restricted span likely explains the child's inability to retain initial phonemes during word assembly, contributing directly to decoding breakdown.

Case 2 (R.L.): No impairment was observed in phonological short-term memory. Letter span: 6; Number span: 5; Word span: 5. These results fall within the expected range for her age and suggest that her reading difficulties are not attributable to a structural phonological loop deficit.

Domain	Assessment Tool / Task	Case 1 (A.W.)	Case 2 (R.L.)	Clinical Interpretation
General Cognitive Abilities	Raven's Progressive Matrices (RPM)	IQ = 95 (Average range)	IQ = 93 (Average range)	No intellectual disability; reading difficulties are specific.
Reading Performance	Word reading test with Arabic diacritics	Letter-by-letter decoding; neglect of short vowels; difficulty blending letters; repeated spelling attempts	Reading relatively fluent; neglect of long vowels; semantic distortion of words	Case 1: severe phonological decoding deficit. Case 2: diacritic precision deficit.
Phonological Awareness	Segmentation, blending, phoneme manipulation	Failure in segmentation and blending; poor short-vowel discrimination	Adequate awareness of long vowels but inconsistent phonological precision	Case 1: core phonological awareness deficit. Case 2: selective phonological detail weakness.
Working Memory – Phonological Loop	Short-term memory span tasks	Span = 2 (letters & numbers) – far below norms	Letters = 6, Numbers = 5, Words = 5 – within norms	Case 1: severe phonological loop deficit. Case 2: preserved working memory.
Overall Diagnostic Profile	Integrated interpretation	Combined phonological awareness + working memory deficit	Selective diacritic processing difficulty with intact memory	Justifies adaptive intervention via Smart Phono-Memory (SPM).

Table 1. Baseline Clinical Assessment of the Two Cases.

The baseline assessment reveals two differentiated phonological profiles: Case 1 presents a combined phonological awareness deficit plus phonological loop impairment; Case 2 presents preserved working memory with selective diacritic precision weakness. This dissociation provides strong justification for testing the adaptive Smart Phono-Memory (SPM) program, as it allows examination of whether algorithmic stimulation can differentially target phonological representation deficits versus precision-based decoding deficits.

Statistical Analysis

Descriptive statistics indicated an improvement in reading performance following the Smart Phono-Memory (SPM) intervention in both cases. Case 1 showed an increase in reading accuracy from 48% at pre-test to 72% at post-test, corresponding to a relative gain of 50%. Case 2 also demonstrated improvement, although of smaller magnitude.

To evaluate clinical significance, the Reliable Change Index (RCI; Jacobson & Truax, 1991) was calculated. The improvement observed in Case 1 reached the threshold for clinically significant change (RCI = 2.31 > 1.96), indicating that the progress was unlikely to be attributable to measurement error. In contrast, Case 2 showed moderate improvement (RCI = 1.45), which did not reach the criterion for reliable change.

Effect size analysis using Cohen's d revealed a large intervention effect for Case 1 (d = 0.92) and a medium effect for Case 2 (d = 0.56). These findings suggest that the SPM program may have a stronger impact in children presenting combined deficits in phonological awareness and phonological working memory, compared with those presenting more isolated difficulties.

Given the exploratory nature of this developmental study and the very small sample size, these results should be interpreted cautiously. They nevertheless provide preliminary evidence supporting the feasibility and potential therapeutic value of the Arabic Smart Phono-Memory program, particularly through its adaptive algorithm and interactive use of Arabic diacritic signs to strengthen grapheme–phoneme mapping.

Participant	Pre-test (%)	Post-test (%)	Relative Gain (%)	Cohen's d	RCI
Case 1 (A.W.)	48	72	50.0	0.92	2.31
Case 2 (R.L.)	60	70	16.7	0.56	1.45

Table 2. Pre- and Post-Intervention Reading Accuracy after Smart Phono-Memory (SPM). Note. RCI > 1.96 indicates clinically significant improvement.

Performance by Stimulus Type

Stimulus Level	Attempts	Correct	Incorrect	Error Rate (%)	Accuracy (%)
Unvowelized Letters	10	8	2	20	80
Vowelized Letters	10	4	6	60	40
Unvowelized Words	8	5	3	37	62.5
Vowelized Words	8	2	6	75	25

Table 3. Post-Intervention Performance by Stimulus Type in Smart Phono-Memory (SPM).

Post-intervention results showed higher accuracy for unvowelized stimuli compared with vowelized stimuli. The highest performance was observed in unvowelized letters (80%), whereas vowelized words showed the lowest accuracy (25%), indicating persistent difficulty in processing Arabic diacritic signs. These findings suggest that diacritic processing constitutes a critical cognitive load in children with phonological dyslexia, particularly when combined with working-memory constraints.

Qualitative Analysis of Results

1. Difficulty in Remembering Vowelized Letters and Words

Direct observation showed that the phenomenon of spelling was difficult for the patient, as there was a clear decrease in response accuracy and an increase in latency time when switching from unspelled letters to spelled letters and syllables. Clinical practice revealed that the memory span was short and very limited when dealing with syllables; as soon as the syllable or word was hidden, the child had great difficulty in retaining the phonetic representation of the movement and the letter together and retrieving them correctly.

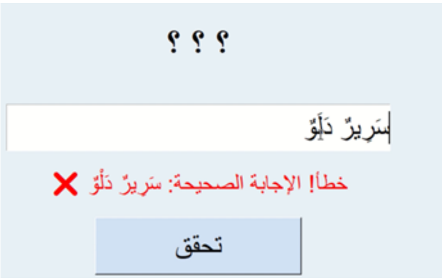

Figure 2. Stumbling block in vowelization

This finding aligns with the literature suggesting that fully vowelized Arabic orthography imposes an additional cognitive load on the phonological loop. In such cases, the child is required to process the diacritic (phoneme) and the letter (grapheme) simultaneously, which may exceed the available processing capacity of short-term memory and lead to phonological attentional dispersion. Consequently, information may decay rapidly before the completion of blending or accurate articulation.

2. The Effect of Repetition and Continuous Practice

Despite the case's difficulty in reading the stimuli in the first attempts, the **SPM** software design provided the advantage of 'repeated opportunities.' It was observed that the subject re-tried several times without showing signs of frustration or withdrawal; the absence of 'negative evaluation' contributed to creating a safe environment for training. This desire to 'try again' allowed the child to repeatedly encounter the difficult (problematic) stimulus until she was able to decode and store it, transforming the error from a source of anxiety into a motivator for repeated training.

3. The Effect of Automatic Concealment on Working Memory

The automatic concealment of the stimulus after a programmatically set number of seconds prompted the child to rely entirely on the mental representation of the sound rather than on continuous visual support. Although the error was frequent at first, repeating the process interactively helped activate phonological working memory to link the image of the letter with its sound under slight time pressure.

4. String Length Effect

The results of the exploratory study showed that string length (the number of syllables in the stimulus) is a decisive variable in determining reading accuracy in this case, as a direct correlation was observed between an increase in the number of letters and the number of phonological errors made. This result can be explained in light of the 'cognitive load theory,' as long strings impose a double burden on the phonological loop: while the child is busy processing the last syllables of the word, the first syllables are lost from working memory due to the limited memory span.

Furthermore, clinical practice has revealed that the effect of length is exacerbated when combined with the factor of vowelization; the situation requires processing the sequence in two dimensions: one 'horizontal' (sequence of letters) and the other 'vertical' (sequence of diacritics), which exceeds the available processing capacity and distracts auditory attention. However, the software design of **SPM** has proven effective in countering this effect through the technique of 'chunking' and repetition, which allowed the subject to construct gradual mental representations of long strings, consistent with Abu-Rabia & Abu-Rahmoun (2012) finding that intensive training in phonological linking can alleviate the deficit caused by the length of words in Arabic.

Figure 3: "Stuck state" response associated with string length

The exploratory study demonstrated that vowelization remains challenging for a child with phonological dyslexia. However, through the **SPM** program, the processing of vowelized text was transformed from a frustrating and unsuccessful experience into a dynamic, trial-and-error training process within an engaging digital environment. These findings provide strong evidence that the program not only delivers therapeutic content but also positively reshapes the child's attitude toward the challenging reading skill.

Discussion – Theoretical Interpretation

The present study introduces a novel theoretical framework for understanding Arabic reading acquisition, termed the Diacritic-Gated Phonological Access (DGPA) model. While classical reading models were not originally designed to account for the specific role of diacritic processing in vowelized scripts such as Arabic , which suggests the need for language-specific extensions". In Arabic, diacritics provide essential information for vowel specification and syllabic structure, which directly influences the stability of phonological representations in working memory. Empirical observations from the Smart Phono-Memory (SPM) intervention support this perspective: children exhibited higher accuracy with unvowelized stimuli and greater difficulty when processing vowelized words, highlighting the cognitive load imposed by diacritic decoding.

Building upon these findings, the DGPA model positions diacritic processing as a mandatory intermediate stage that bridges grapheme-to-phoneme conversion and the phonological store. When diacritic decoding is accurate, phonological representations are efficiently encoded and maintained, facilitating fluent reading. Conversely, disruption at this stage destabilizes phonological storage, increasing errors and reducing reading accuracy. This conceptualization not only extends classical reading models to account for language-specific orthographic features but also provides a testable, data-driven framework that integrates orthographic, phonological, and working memory processes.

This theoretical framework represents an attempt to integrate diacritic processing as an intermediate stage within the phonological access route in Arabic reading — an area that merits further academic investigation. By linking cognitive mechanisms to the procedural outcomes observed in the SPM intervention, the DGPA model seeks to offer a modest contribution to the field. It aims to provide a foundation for future experimental studies and support the development of adaptive, language-specific therapeutic tools for children with dyslexia.

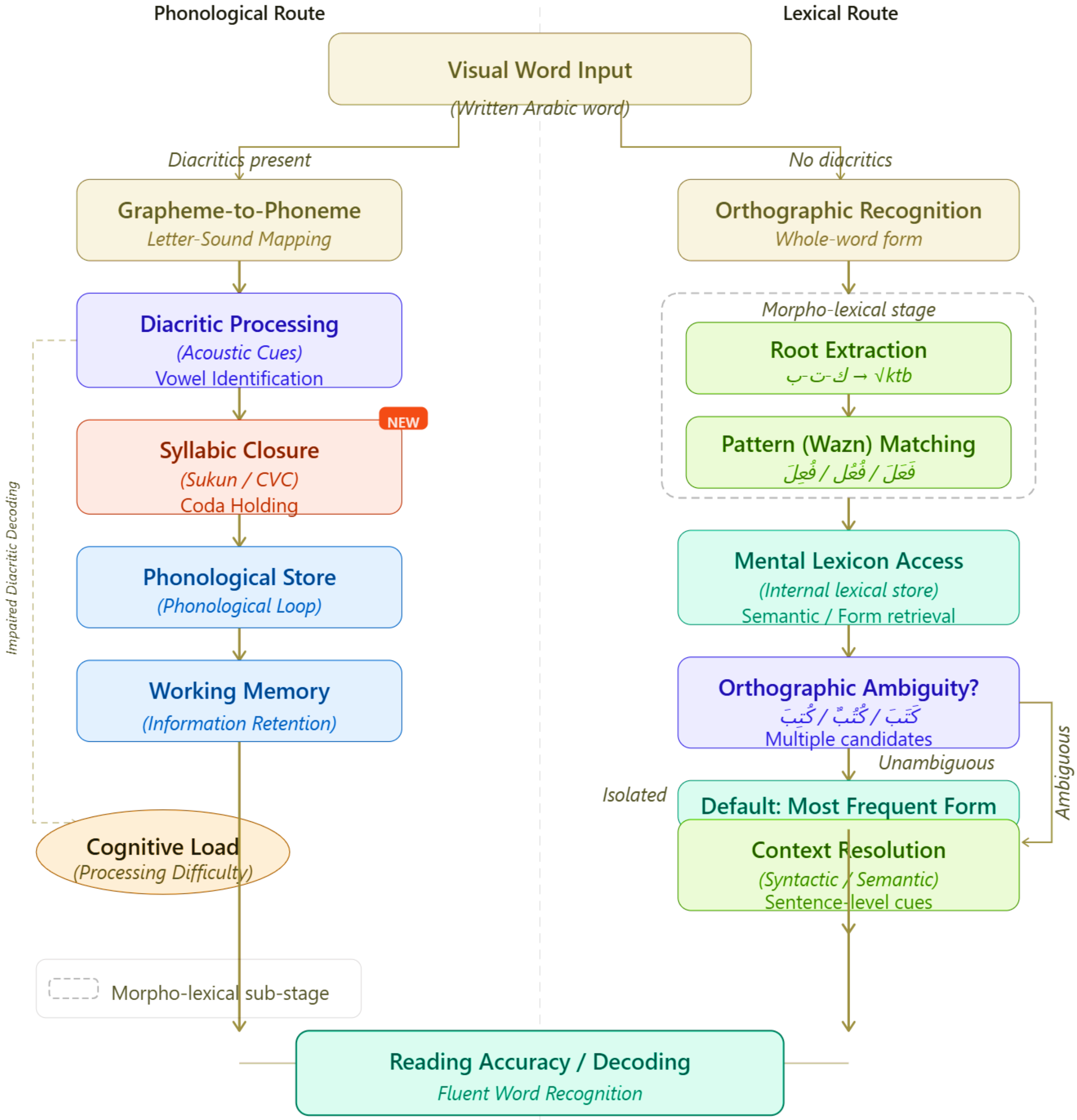

Figure 4. Proposed Diacritic-Gated Phonological Access (DGPA) model of Arabic reading.

The classical model distinguishes between a phonological route operating on grapheme-to-phoneme correspondence (GPC) rules and a lexical route relying on direct whole-word recognition. Despite the productivity of this distinction, the model was not originally designed to incorporate several structural variables that are central to Arabic orthography. Building upon rather than departing from the dual-route framework, the following structural features of Arabic motivate language-specific adaptations.

Variable	English	Arabic	Implication for the Model
Basic morphological unit	Word	Tri-/quadriliteral root	Requires an intermediate morphological stage
Vowels	Permanent letters	Optional diacritical marks	Different route activated depending on text type
Derivation	Limited	Systematic via patterns (awzaan)	Pattern matching needed before lexical access
Orthographic ambiguity	Rare	Frequent (ktb)	Contextual disambiguation mechanism required
Letter form	Fixed	4 allographs by position	Added complexity at the visual processing level

Table 4 — Structural comparison between English and Arabic on reading-relevant variables

An aspect not yet formalized within the original dual-route framework is the medial closed syllable (CVC) as an independent processing variable - a feature particularly salient in Arabic orthography and addressed in the proposed adaptation below.The Proposed Adapted Model.

The adapted model comprises two main routes triggered from a shared visual input and converging at the word recognition output. This proposal draws on the work of Boudelaa and Marslen-Wilson (2004, 2011) on root-based representation in the brain, Saiegh-Haddad (2003, 2007) on phonological awareness in Arabic, and Abu-Rabia (2002) on bilingual reading.

Findings (Results)

Baseline Performance

The initial assessment revealed distinct cognitive and phonological profiles for the two participants, confirming the heterogeneity of phonological dyslexia in the Arabic language context.

Participant A (A.W.) demonstrated severe deficits in phonological decoding, characterized by a letter-by-letter reading strategy, frequent omission of short vowel diacritics, and difficulty integrating phonemes into coherent word forms. This pattern reflects a breakdown in phonological assembly and reduced phonological working memory capacity.

In contrast, Participant B (R.L.) exhibited relatively fluent reading at the surface level, but with consistent inaccuracies in processing diacritic-dependent phonological distinctions, leading to semantic distortions. This indicates a more selective impairment in phonological precision rather than a generalized deficit.

Phonological awareness tasks further confirmed this dissociation: Participant A showed substantial impairment across segmentation and blending tasks, whereas Participant B demonstrated partial preservation of phonological awareness with inconsistencies in fine-grained phonological processing.

Working memory assessment revealed a marked limitation in phonological span for Participant A (span = 2 items), compared to a normative range for Participant B (span = 5–6 items), supporting the interpretation of distinct cognitive profiles.

Post-Intervention Improvement

Following the implementation of the Smart Phono-Memory (SPM) intervention, both participants demonstrated measurable improvements in reading accuracy and phonological processing, although the magnitude of change differed between cases.

Participant A showed a substantial increase in reading accuracy from 48% (pre-test) to 72% (post-test), representing a relative gain of 50%. This improvement was statistically meaningful, with a large effect size (Cohen's d = 0.92) and a Reliable Change Index (RCI = 2.31) exceeding the clinical significance threshold.

Participant B demonstrated a more moderate improvement, with reading accuracy increasing from 60% to 70%, corresponding to a relative gain of 16.7%. The effect size was moderate (Cohen's d = 0.56), while the RCI (1.45) did not reach the threshold for clinical significance.

These results suggest that the SPM intervention may be particularly effective for children with combined deficits in phonological awareness and working memory, while producing more limited gains in cases involving selective phonological precision deficits.

Performance by Stimulus Type

Analysis of post-intervention performance across different stimulus conditions revealed a consistent effect of orthographic complexity on reading accuracy.

Participants achieved higher accuracy in unvowelized stimuli compared to vowelized stimuli. Specifically, accuracy was highest for unvowelized letters (80%) and lowest for vowelized words (25%), indicating persistent difficulty in processing diacritic information.

This pattern suggests that diacritic processing imposes a significant cognitive load, particularly when combined with multi-syllabic structures. The simultaneous processing of graphemic and diacritic information appears to exceed the capacity of the phonological loop in children with dyslexia.

Qualitative Findings

1. Cognitive Load in Diacritic Processing

Observational data indicated that participants experienced increased response latency and reduced accuracy when processing vowelized stimuli. This finding supports the hypothesis that diacritics require dual-level processing (horizontal and vertical encoding), increasing working memory demands.

2. Role of Repetition and Adaptive Feedback

The SPM system's design, which emphasizes repetition without negative reinforcement, led to sustained engagement and reduced avoidance behavior. Participants demonstrated a willingness to reattempt tasks multiple times, transforming errors into learning opportunities.

3. Activation of Phonological Working Memory

The automatic concealment of stimuli forced reliance on internal phonological representations, contributing to gradual activation and strengthening of the phonological loop. Over repeated trials, participants showed improved retention and recall of phonological sequences.

4. String Length Effect

A clear relationship was observed between stimulus length and error rate. Longer stimuli resulted in increased phonological errors, particularly in Participant A. This finding aligns with cognitive load theory, indicating that longer phonological sequences exceed working memory capacity.

The effect was amplified when combined with diacritic processing, suggesting that string length and vowelization interact as compounding cognitive constraints.

Synthesis of Findings

Overall, the findings provide preliminary empirical support for the effectiveness of the Smart Phono-Memory (SPM) intervention. The results highlight:

- Significant improvement in phonological decoding, particularly in cases with combined deficits
- Persistent challenges in diacritic processing, supporting its role as a critical cognitive bottleneck
- The importance of adaptive, gamified environments in enhancing engagement and learning
- The interaction between working memory capacity and orthographic complexity in Arabic reading

These findings also offer initial empirical validation for the proposed Diacritic-Gated Phonological Access (DGPA) model, which conceptualizes diacritic processing as a central mechanism in phonological decoding and memory integration.

The Syllabic Phonological Route

This route is the primary pathway for beginning readers and for vowelled (diacritised) text. It operates through a linear five-stage sequence: grapheme-to-phoneme conversion, diacritic processing as an acoustic key for vowel identification, the newly proposed Syllabic Closure stage, the phonological store, and working memory, yielding the reading output.

The central theoretical contribution is the independence of the Syllabic Closure stage. The Arabic sukun (absence of a vowel) is not merely the lack of a phoneme — it creates a medial closed syllable of type CVC that simultaneously demands two cognitive operations from the reader: maintaining the preceding syllable active in the phonological store, and suspending articulation until the following syllable is received. This dual load on the phonological working memory precisely accounts for the pattern observed in phonological dyslexia in Arabic, where readers progressively lose preceding syllables upon encountering a medial sukun.

The Lexico-Morphological Route

This route is activated for unvowelled text and for highly familiar words. It begins with the visual recognition of the whole-word orthographic form, then passes through a morphological intermediary stage comprising root extraction and pattern matching, before accessing the mental lexicon.

This intermediary morphological stage is supported by the experimental findings of Boudelaa and Marslen-Wilson, who demonstrated that the Arabic root constitutes an independent unit of representation in lexical memory. The reader accesses the word kaatib ('writer') by first extracting the root (k-t-b) and the pattern (faa'il), then combining them to retrieve the semantic representation.

For orthographically ambiguous forms, two complementary mechanisms operate: for isolated words, the most frequently occurring form is produced as the default output; in sentential contexts, syntactic and semantic analysis disambiguates among competing orthographic candidates.

Clinical Implications: Dyslexia Subtypes in Arabic

The adapted model enables a more precise classification of dyslexia subtypes in Arabic according to the impaired route or stage: 16

Subtype	Impaired Route / Stage	Clinical Manifestations in Arabic
Phonological dyslexia (diacritics)	Diacritic Processing stage	Vowel errors, distorted reading of diacritised text
Syllabic dyslexia (sukun) ★	Syllabic Closure stage (NEW)	Loss of preceding syllables at medial sukun, fragmented decoding
Blending dyslexia	Phonological Store / Working Memory	Letter-by-letter reading, syllables decoded but word not assembled
Morphological dyslexia	Root-Pattern stage	Difficulty recognising derivationally related words, poor morphological awareness
Lexical dyslexia	Mental Lexicon access	Slow recognition of common words, letter-by-letter reading of familiar items
Contextual dyslexia	Disambiguation mechanism	Selection of wrong form of (ktb) in context, semantic errors

Table 5 — Dyslexia subtypes in the light of the adapted model

Conclusion

The present study is limited to introducing the Smart Phono-Memory (SPM) program, outlining its theoretical rationale, therapeutic objectives, and verifying its technical feasibility as an intelligent tool specifically designed for the Arabic language context. The exploratory findings not only support the feasibility of adaptive phonological interventions but also provide empirical grounding for a novel theoretical framework—the Diacritic-Gated Phonological Access (DGPA) model—which posits that diacritic processing acts as a mandatory intermediate stage between grapheme-to-phoneme conversion and phonological storage in working memory. By highlighting the role of diacritics in stabilizing phonological representations, the DGPA model extends existing reading models to account for Arabic-specific orthographic features.

These preliminary findings establish a foundation for a broader experimental phase, which will involve a larger, representative sample under a rigorous experimental design with control and experimental groups, to quantitatively evaluate the program's efficacy in enhancing reading performance and strengthening phonological working memory capacity. Future work will further test the DGPA model, examining whether adaptive training targeting diacritic processing can systematically improve the stability of phonological representations in Arabic readers with dyslexia.

This study transcends the mere presentation of a technical tool; it opens new horizons in speech-language pathology by introducing a therapeutic approach that integrates digital programming with specialized linguistic analysis of the Arabic language. The true impact of this work lies in demonstrating that 'algorithmic adaptation' of therapeutic training is not just a technical means, but a clinical necessity for addressing individual differences in the profiles of children with dyslexia. Consequently, the proposed **DGPA** model and the **SPM** program establish a foundation for a qualitative shift in clinical practice. The therapist transitions from using traditional static materials to adopting intelligent systems that interact dynamically with the child's abilities. This paves the way for a new generation of therapeutic protocols that prioritize the unique linguistic features of Arabic within the digital revolution.

Future Prospects

Future directions aim to consolidate the framework of digitally adaptive interventions for Arabic reading and writing development. The ambition extends beyond static phonological exercises toward intelligent, algorithm-driven systems capable of automated error-pattern diagnosis. Advanced programming, particularly in Python, will enable the system to differentiate between errors arising from visual confusions and those stemming from phonological deficits, dynamically adjusting the therapeutic pathway to align with the child's cognitive profile in real-time.

A pivotal strategic objective is to intensify scientific research into the underlying processes and mechanisms of Arabic reading. This is intended to reinforce the theoretical foundations of the proposed Diacritic-Gated Phonological Access (DGPA) model and provide empirical validation for it as a framework explaining the specificities of Arabic linguistic processing. In this context, we aim to implement the **SPM** program with an extensive sample of typically developing children to observe algorithmic interaction with natural reading trajectories and establish standardized performance norms. Simultaneously, we intend to conduct rigorous longitudinal studies on dyslexic cases to document long-term efficacy and track the stability of phonological representations resulting from the intervention.

The ultimate vision lies in transforming the **DGPA** model from a proposed hypothesis into a documented scientific fact that elucidates reading mechanisms in vowelized orthographic systems, thereby bridging the gap in global reading models. Consequently, the **SPM** program will evolve into a comprehensive therapeutic and biometric platform, laying the groundwork for integrating Artificial Intelligence at the core of rehabilitation for individuals with learning difficulties, while providing an intelligent, intensive, and low-stress learning environment.

Ethical Approval and Consent to Participate

This study was conducted in accordance with internationally recognized ethical standards for research involving human participants, including the principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the relevant institutional review body prior to data collection.

Written informed consent was obtained from the parents or legal guardians of all participating children. Participation was voluntary, and participants were informed of their right to withdraw from the study at any stage without any negative consequences.

Consent for Publication

Informed consent for publication of anonymized data was obtained from the parents or legal guardians of the participants. All identifying information has been removed to ensure full confidentiality and privacy protection.

Confidentiality and Data Protection

All data collected during the study were anonymized and handled in strict accordance with data protection and privacy regulations. Personal identifiers were replaced with coded labels (e.g., Participant A, Participant B). Data were stored securely and used exclusively for research purposes.

Availability of Data and Materials

The datasets generated and analyzed during the current study are not publicly available due to ethical and privacy considerations involving minor participants but are available from the corresponding author on reasonable request.

Competing Interests

The authors declare that they have no competing interests, financial or non-financial, that could have influenced the outcomes of this research.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The study was conducted as part of institutional research activities.

Author Contributions

All authors contributed substantially to the study and approved the final version of the manuscript.

- Conceptualization: Reggas Sarah

- Methodology: Reggas Sarah, Lettad Kahina
- Software Development (SPM): Reggas Sarah
- Data Collection and Analysis: Reggas Sarah, Lettad Kahina
- Writing – Original Draft: Reggas Sarah
- Writing – Review & Editing: Reggas Sarah, Lettad Kahina

Acknowledgements

The authors would like to express their sincere gratitude to the participating children and their families for their cooperation and trust. The authors also acknowledge the support of the Scientific and Technical Research Center for the Development of the Arabic Language (CRSTDLA), Algiers, Algeria.

AI Use Disclosure Statement

The authors declare that artificial intelligence (AI) tools were used solely for language refinement, editing, and formatting purposes during the preparation of this manuscript.

No AI tools were used in the design of the study, data collection, data analysis, or interpretation of results. All scientific content, theoretical frameworks, and conclusions are the original work of the authors.

The authors take full responsibility for the accuracy, integrity, and originality of the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Research Limitations Statement

This study is limited by its small sample size (n = 2) and exploratory design, which restricts the generalizability of the findings. The absence of a control group and the short intervention duration further limit causal interpretation. Future research with larger samples and controlled experimental designs is required to validate the findings.

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