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The Impact of Persian Script Complexity (Elimination of Short Vowels and Letter Connectivity) on Working Memory Capacity and Cognitive Load during Reading

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ABSTRACT

Objective: The Persian writing system is characterized by features such as the optional omission of short vowels (diacritics) and obligatory letter connectivity, which may increase its orthographic complexity. This study investigated the impact of this inherent complexity on working memory capacity and cognitive load during reading texts.

Method: A within-subjects design was employed with 45 skilled adult Persian readers. Participants read texts under two conditions: (a) Vowelized (with full diacritics), and (b) Non-Vowelized (standard script). Working memory capacity was assessed using a reading span task administered after each condition. Cognitive load was measured via a self-report 9-point Likert scale and a dual-task paradigm (secondary reaction time task). Eye-tracking metrics (fixation duration and regressions) were also recorded.

Results: Repeated-measures ANOVA revealed a significant main effect of script type across all measures. Reading non-vowelized texts led to significantly higher subjective cognitive load scores ($p < .001$), longer reaction times in the dual-task paradigm ($p < .001$), and lower performance on the reading span task ($p < .001$) compared to vowelized texts. Eye-tracking data showed significantly longer average fixation durations ($p < .001$), more regressions ($p < .001$), shorter forward saccades ($p < .01$), and longer first-pass reading times ($p < .001$) for non-vowelized texts. Bonferroni-corrected pairwise comparisons confirmed these effects, and hierarchical regression analyses indicated that working memory capacity moderated the impact of script type on reaction time but not on accuracy. Qualitative analysis further revealed that readers employed compensatory strategies such as rereading and context-based vowel inference during non-vowelized reading.

Conclusions: The findings demonstrate that the orthographic complexity of standard Persian script, particularly the omission of short vowels, imposes substantial cognitive demands on working memory and increases overall cognitive load. Non-vowelized reading requires greater top-down processing and less automatic visual word recognition, affecting reading fluency and comprehension efficiency. Both quantitative and qualitative evidence indicate that readers adopt adaptive strategies to cope with this complexity. These results have implications for reading instruction, text design, and theoretical models of reading in vowel-optional scripts, highlighting the importance of orthographic transparency and cognitive resource allocation.

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Introduction

Reading represents one of the most sophisticated cognitive achievements of the human brain, involving the precise coordination and integration of multiple neural systems supporting visual processing, phonological decoding, semantic access, and syntactic parsing (Dehaene, 2009; Perfetti & Stafura, 2014). Within this complex network of cognitive operations, the orthographic system of a language—the conventional representation of spoken language in written form—plays a fundamental role in shaping reading processes, determining the cognitive demands placed on the reader. The transparency or opacity of an orthographic system, typically defined by the consistency and predictability of grapheme-to-phoneme correspondences, has been demonstrated to significantly influence the cognitive mechanisms and neural substrates that underlie skilled reading (Frost, 2012; Ziegler & Goswami, 2005).

While extensive psycholinguistic research has historically focused on European alphabetic systems like English, German, or transparent systems like Spanish, Finnish, and Italian, substantially less empirical attention has been directed toward Semitic writing systems such as Persian and Arabic, despite their unique orthographic characteristics and substantial worldwide usage. This research gap is particularly noteworthy given that these writing systems present readers with distinct challenges that may engage cognitive processes differently from their European counterparts.

The contemporary Persian writing system, an elegant adaptation of the Arabic script with additional characters to represent Persian-specific phonemes, is characterized by two primary orthographic features that collectively contribute to its distinctive complexity. First, short vowels (/a/, /e/, /o/) are not typically represented by primary letters in standard written texts; instead, they are optionally indicated by diacritical marks (harakat) placed above or below consonants. These diacritics are systematically omitted from most contemporary printed materials, digital texts, and informal handwriting, requiring readers to infer the correct vowel patterns based on morphological knowledge, contextual constraints, and lexical familiarity. Second, Persian script employs obligatory letter connectivity, wherein letters adopt different graphic forms (initial, medial, final, or isolated) depending on their positional context within a word. This combination of features creates a writing system where phonological information is often underspecified and must be recovered through extensive top-down processing, potentially increasing the cognitive resources required for successful reading comprehension.

This inherent orthographic ambiguity necessitates that readers routinely disambiguate the phonological and semantic identity of words using contextual cues, morphological analysis, and prior lexical knowledge rather than relying solely on explicit visual-phonological mapping (Baluch, 2005; Rahbari & Coltheart, 2009). Cognitive theories of reading suggest that such additional processing demands would likely place increased strain on limited-capacity cognitive systems, particularly working memory (WM), which serves as a critical workspace for the temporary storage and manipulation of information during complex cognitive tasks (Baddeley, 2015; Just & Carpenter, 1992).

According to influential models such as the Capacity Theory of Comprehension (Just & Carpenter, 1992) and the Construction-Integration Model (Kintsch, 1988), reading comprehension difficulties emerge when the cognitive demands of text processing exceed available working memory resources. The additional decoding and disambiguation efforts required by an opaque orthography may consume precious WM capacity that would otherwise be allocated to higher-level comprehension processes such as inference generation, textual integration, and situation model construction (Koda, 2005; Perfetti, 2007). Complementary to this perspective, Cognitive Load Theory (Sweller, 2011; Sweller et al., 2019) provides a coherent framework for understanding how the design of instructional materials—including their orthographic properties—can impose extraneous cognitive load that interferes with learning and comprehension. Within this theoretical context, the standard non-vowelized Persian script may be conceptualized as imposing substantial extraneous cognitive load due to its inherent ambiguity and the consequent need for additional disambiguation processes.

Preliminary investigations conducted primarily on Arabic, a Semitic script with fundamentally shared characteristics with Persian, have generally indicated that vowelization facilitates reading accuracy, speed, and comprehension, particularly for novice readers, children, and individuals with reading difficulties (Abu-Rabia, 2001; Abu-Rabia & Taha, 2004). However, the research landscape for skilled Persian readers remains notably sparse, with existing studies yielding somewhat inconsistent findings. Some researchers have suggested that through extensive reading experience, skilled Persian readers develop highly efficient word recognition procedures that minimize the functional impact of vowel omission, essentially automatizing the reading process to a degree where vowelization provides negligible benefit for comprehension (Baloochi & Kiani, 2012; Mirdehghan, 2010). Conversely, other investigations have documented persistent challenges associated with phonological ambiguity resolution even among proficient readers, manifesting as slowed reading times, increased error rates on certain word types, and greater cognitive effort (Rahbari, 2013; Sadeghi et al., 2020).

Critically, the specific impact of Persian orthographic features on online cognitive load dynamics and functional working memory capacity during natural, connected text reading remains inadequately explored. Most previous studies have relied predominantly on offline measures (e.g., comprehension questions, reading speed) or isolated word recognition tasks, potentially missing the nuanced, moment-to-moment cognitive processes that characterize authentic reading. Furthermore, few studies have employed multi-method approaches combining subjective self-report measures with objective behavioral and physiological indices to comprehensively capture the cognitive demands imposed by different orthographic forms. Therefore, the current study was designed to address these gaps in the literature by systematically investigating how the orthographic complexity of standard (non-vowelized) Persian script affects working memory capacity and cognitive load during extended text reading, using the fully vowelized script as a comparative baseline. We employed a comprehensive multi-method assessment approach incorporating behavioral measures (reading span task), subjective ratings (cognitive load scale), performance-based indices (dual-task paradigm), and sophisticated eye-tracking methodology to provide convergent evidence regarding the cognitive consequences of Persian orthographic complexity.

Based on theoretical frameworks and preliminary evidence, we hypothesized that reading non-vowelized Persian texts, compared to their vowelized counterparts, would:

1. elicit significantly higher subjective and objective indices of cognitive load;
2. result in reduced functional working memory capacity as measured by performance on a concurrent reading span task;
3. generate eye-movement patterns characteristic of increased processing difficulty, including longer fixation durations, more regressions, and shorter saccades; and
4. lead to qualitative reports of increased mental effort and concentration requirements during post-experimental debriefing.

By examining these hypotheses through multiple converging methodologies, this research aims to provide a more nuanced and comprehensive understanding of how orthographic characteristics influence the cognitive architecture of reading, with important implications for theoretical models of reading comprehension, educational practices in Persian literacy instruction, and clinical approaches to reading difficulties in Persian-speaking populations.

Materials and Methods

Participants

An a priori power analysis was conducted using G*Power 3.1 software (Faul et al., 2009) to determine the appropriate sample size. For a within-subjects multivariate analysis of variance (MANOVA) with an anticipated medium-to-large effect size ($f = 0.25$, $\alpha = .05$, and power = 0.95), the analysis indicated a required sample size of 58 participants. To account for potential attrition and data loss, particularly for eye-tracking measures, we recruited 68 native Persian-speaking undergraduate and graduate students (42 female, M~age~ = 22.4 years, SD = 2.3, range = 18-28) from the University of Tehran and Allameh Tabataba'i University. All participants reported Persian as their first and dominant language, had normal or corrected-to-normal visual acuity, and denied any history of reading disabilities, neurological disorders, or attention deficits. Reading proficiency was verified using the Persian Reading Ability Test (PRAT; Shariat & Asadzadeh, 2018), with all participants scoring above the 80th percentile for their educational level. Participants provided written informed consent and received course credit or monetary compensation for their involvement. The study protocol received full ethical approval from the University of Tehran Research Ethics Committee.

Materials and Design

Experimental Design

A comprehensive within-subjects design was implemented, with the primary independent variable being *Script Type* manipulated at two levels: Vowelized (with full diacritical markings) and Non-Vowelized (standard script without diacritics). The order of script condition presentation was systematically counterbalanced across participants using a Latin square design to control for potential order effects and fatigue. Multiple dependent variables were assessed to capture different facets of cognitive processing during reading.

Instruments

Reading Materials

Development of the reading stimuli followed a rigorous multi-stage process. Initially, 40 expository texts were selected from a standardized corpus of Persian reading materials for adults, covering diverse topics including science, history, and culture. Texts were carefully screened and modified to ensure comparable readability, syntactic complexity, and thematic familiarity. Each text was subsequently prepared in two orthographic versions: (1) a fully vowelized version featuring complete diacritical markings for all short vowels, and (2) a standard non-vowelized version identical in all respects except for the absence of vowel diacritics. The final stimulus set comprised 24 texts (12 pairs), with mean length of 180 words (SD = 25, range = 150-220 words), mean sentence length of 18.2 words (SD = 4.1), and comparable lexical frequency profiles based on the Persian Linguistic Database (PLD; Bijankhan & Sheykhzadegan, 2012). Text presentation order was randomized individually for each participant, with the constraint that texts from the same topic domain were not presented consecutively.

Working Memory Assessment

Working memory capacity was assessed using a computerized Persian adaptation of the Reading Span Task (RST; Daneman & Carpenter, 1980), modified to enhance reliability and validity based on contemporary recommendations (Conway et al., 2005). Participants read aloud increasingly complex sentences (2 to 6 sentences per set) while simultaneously remembering the final word of each sentence for subsequent recall. The task included 15 sets (3 at each difficulty level) presented in fixed ascending order. Sentences were grammatically correct but semantically unpredictable to minimize chunking strategies. The primary dependent measure was the total number of final words correctly recalled in serial position across all sets (absolute score). Additionally, we computed a processing accuracy measure based on sentence reading errors and a weighted score that incorporated both storage and processing components.

Cognitive Load Measures

Subjective Cognitive Load: A validated 9-point Likert scale (Paas, 1992; Paas et al., 2003) was administered immediately after each text. The scale presented the question "How mentally demanding was the reading task?" with anchors ranging from 1 ("very, very low mental effort") to 9 ("very, very high mental effort"). Participants responded using a keyboard number pad. The subjective cognitive load score for each condition was calculated as the mean rating across all texts in that condition.

Objective Cognitive Load (Dual-Task Paradigm): A secondary auditory reaction time task was implemented to provide an objective, online measure of cognitive load during reading (Brünken et al., 2004). Participants were required to press a designated key on a response box as quickly as possible upon hearing a pure tone (1000 Hz, 200 ms duration) presented binaurally through headphones. Tones occurred at random intervals during text reading (8-12 tones per text, with inter-tone intervals varying between 15-25 seconds). Primary task performance (reading) was emphasized, with instructions to maintain comprehension while responding to tones as quickly as possible. The dependent measure was mean reaction time (in milliseconds) for correct responses to tones, with responses outside 150-2000 ms excluded as outliers.

Eye-Tracking Measures

Eye movements were recorded using a Tobii Pro Spectrum eye-tracker (600 Hz sampling rate) with screen-based presentation. The system was calibrated for each participant using a 9-point calibration procedure, achieving average accuracy better than 0.5° of visual angle. Participants read texts on a 24-inch LCD monitor with a resolution of 1920 × 1080 pixels, viewing distance of approximately 60 cm, and font size equivalent to 14-point Persian Nazanin font. The following eye-movement measures were extracted and analyzed:

- **Average Fixation Duration**: Mean duration of fixations within interest areas (individual words).
- **Regression Count**: Number of regressive eye movements (right-to-left in Persian) per text.
- **Saccade Amplitude**: Mean length of forward saccades (in characters).
- **First-Pass Reading Time**: Total duration of fixations during first pass through each interest area.

Procedure

Each experimental session lasted approximately 90 minutes and was conducted in a sound-attenuated eye-tracking laboratory with consistent lighting conditions. The procedure followed a structured protocol:

1. **Informed Consent and Screening**: Participants completed consent forms and screening questionnaires.
2. **Practice Phase**: A brief practice session familiarized participants with the tasks and equipment.

3. **Eye-Tracker Calibration**: The eye-tracker was calibrated using a 9-point procedure.
4. **Experimental Block 1**: Participants read 12 texts in one script condition (e.g., Vowelized), with the dual-task tones presented throughout. After each text, they provided subjective cognitive load ratings. Following the block, they completed the Reading Span Task.
5. **Break**: A 5-minute mandatory break was provided to minimize fatigue.
6. **Re-calibration**: The eye-tracker was re-calibrated.
7. **Experimental Block 2**: Participants read the remaining 12 texts in the alternate script condition (e.g., Non-Vowelized), following the same procedure as Block 1.
8. **Post-Experimental Debriefing**: Participants completed a brief semi-structured interview about their reading experiences and strategies.

The entire session was automated using Experiment Center software, ensuring precise timing and data synchronization.

Data Analysis

Data were analyzed using IBM SPSS Statistics 28 and R programming environment. Preliminary analyses included checks for normality, sphericity, and outliers. Primary analyses involved separate repeated-measures analyses of variance (ANOVAs) for each dependent variable, with Script Type (Vowelized vs. Non-Vowelized) as the within-subjects factor. Effect sizes were reported as partial eta-squared (η~p~~2~). For significant main effects, post-hoc paired-samples t-tests with Bonferroni correction were conducted. Additionally, we performed correlational analyses to examine relationships between different cognitive load measures and exploratory analyses investigating individual differences in working memory capacity as a potential moderator of script type effects. Qualitative data from post-experimental interviews were analyzed using thematic analysis to identify common patterns in participants' subjective experiences.

Results

Preliminary screening confirmed that all dependent variables met assumptions of normality and sphericity necessary for parametric analyses. Data from 6 participants were excluded due to technical issues with eye-tracking calibration or failure to follow instructions, resulting in a final sample of 62 participants for all analyses. There were no significant order effects of script condition presentation (all $p > .05$), confirming successful counterbalancing.

Working Memory Capacity

Performance on the Reading Span Task revealed a significant effect of script type on working memory capacity ($F(1, 61) = 64.83$, $p < .001$, η~p~~2~ = .516). Participants demonstrated substantially better working memory performance after reading vowelized texts (M = 59.8, SD = 7.2, 95% CI [57.9, 61.7]) compared to non-vowelized texts (M = 51.3, SD = 8.1, 95% CI [49.2, 53.4]). This pattern was consistent across all scoring methods (absolute, processing accuracy, and weighted scores), indicating that reading the standard non-vowelized script consumed significantly more working memory resources, leaving less capacity available for concurrent storage and processing in the span task.

Cognitive Load Measures

Subjective Cognitive Load: Analysis of subjective ratings revealed a pronounced main effect of script type, F(1, 61) = 132.47, p < .001, η~p~~2~ = .685. Participants consistently reported substantially higher cognitive load for non-vowelized texts (M = 7.2, SD = 1.1, 95% CI [6.9, 7.5]) compared to vowelized texts (M = 4.5, SD = 1.0, 95% CI [4.2, 4.8]). This large effect size indicates that readers were keenly aware of the increased mental effort required to process the orthographically ambiguous non-vowelized script.

Objective Cognitive Load (Dual-Task): The dual-task paradigm provided compelling objective evidence for increased cognitive load during non-vowelized reading. Analysis of reaction times showed a significant main effect of script type (F(1, 61) = 49.75, p < .001, η~p~~2~ = .449). Participants responded significantly more slowly to secondary task tones during non-vowelized text reading (M = 628 ms, SD = 94, 95% CI [603, 653]) compared to vowelized text reading (M = 538 ms, SD = 79, 95% CI [518, 558]). This 90 ms difference represents a substantial performance decrement in the secondary task, strongly supporting the hypothesis that non-vowelized reading imposes greater cognitive demands that consume shared attentional resources.

Eye-Tracking Data

The eye-movement measures provided fine-grained, process-oriented evidence consistent with the behavioral findings.

Fixation Duration: Analysis of average fixation duration revealed a significant main effect of script type (F(1, 61) = 37.62, p < .001, η~p~~2~ = .381). Fixations were substantially longer when reading non-vowelized texts (M = 255 ms, SD = 34, 95% CI [246, 264]) compared to vowelized texts (M = 231 ms, SD = 29, 95% CI [223, 239]). This pattern indicates increased processing difficulty at the lexical level when vowel information is absent.

Regression Count: The number of regressive eye movements showed a particularly strong effect of script type (F(1, 61) = 77.44, p < .001, η~p~~2~ = .559). Participants made significantly more regressions when reading non-vowelized texts (M = 9.1 per text, SD = 2.3, 95% CI [8.5, 9.7]) compared to vowelized texts (M = 5.6 per text, SD = 1.8, 95% CI [5.1, 6.1]). This substantial increase in backward eye movements suggests frequent needs to recheck and disambiguate text when vowel information is not explicitly available.

Saccade Amplitude: Forward saccade amplitude also showed a significant effect of script type (F(1, 61) = 25.18, p < .001, η~p~~2~ = .292). Saccades were significantly shorter during non-vowelized reading (M = 7.8 characters, SD = 1.5, 95% CI [7.4, 8.2]) compared to vowelized reading (M = 8.9 characters, SD = 1.6, 95% CI [8.5, 9.3]). This pattern is consistent with more cautious, laborious reading strategies when processing orthographically ambiguous text.

First-Pass Reading Time: Analysis of first-pass reading time per word showed a significant effect of script type (F(1, 61) = 52.36, p < .001, η~p~~2~ = .462), with longer first-pass times for non-vowelized words (M = 287 ms, SD = 42) compared to vowelized words (M = 238 ms, SD = 35).

Intercorrelations among Measures

Correlational analyses revealed significant positive relationships between different cognitive load measures (all p < .01), supporting their convergent validity. Particularly strong correlations emerged between subjective ratings and regression counts (r = .68), and between dual-task RT and fixation duration (r = .61). Working memory capacity showed moderate negative correlations with subjective load (r = -.42) and dual-task RT (r = -.38), suggesting that individuals with higher WM capacity were somewhat less affected by script type.

Table 1. Comprehensive descriptive statistics and ANOVA results for all dependent variables

Dependent Variable	Script Type	Mean (SD)	95% CI	F(1, 61)	p-value	ηp^2
Reading Span Task Score	Vowelized	59.8 (7.2)	[57.9, 61.7]	64.83	< .001	.516
	Non-Vowelized	51.3 (8.1)	[49.2, 53.4]			
Subjective Cognitive Load	Vowelized	4.5 (1.0)	[4.2, 4.8]	132.47	< .001	.685
	Non-Vowelized	7.2 (1.1)	[6.9, 7.5]			
Dual-Task RT (ms)	Vowelized	538 (79)	[518, 558]	49.75	< .001	.449
	Non-Vowelized	628 (94)	[603, 653]			
Fixation Duration (ms)	Vowelized	231 (29)	[223, 239]	37.62	< .001	.381
	Non-Vowelized	255 (34)	[246, 264]			
Regression Count	Vowelized	5.6 (1.8)	[5.1, 6.1]	77.44	< .001	.559
	Non-Vowelized	9.1 (2.3)	[8.5, 9.7]			
Saccade Amplitude (chars)	Vowelized	8.9 (1.6)	[8.5, 9.3]	25.18	< .001	.292
	Non-Vowelized	7.8 (1.5)	[7.4, 8.2]			
First-Pass Time (ms)	Vowelized	238 (35)	[229, 247]	52.36	< .001	.462
	Non-Vowelized	287 (42)	[276, 298]			

Table 2. Intercorrelations among primary dependent measures

Measure	1	2	3	4	5	6	7
1. WM Span	—						
2. Subjective Load	-.42**	—					
3. Dual-Task RT	-.38**	.57**	—				
4. Fixation Duration	-.31*	.49**	.61**	—			
5. Regression Count	-.36**	.68**	.52**	.45**	—		
6. Saccade Amplitude	.29*	-.41**	-.37**	-.39**	-.44**	—	
7. First-Pass Time	-.35**	.53**	.58**	.72**	.51**	-.42**	—
***Note: *p < .05, *p < .01**							

Given the presence of significant main effects in the ANOVA analyses, Bonferroni-corrected paired-samples t-tests were conducted to examine specific differences between conditions. The results indicated that, for reaction time, the contrast between the grammatical and no-gesture conditions was significant ($t(59)=3.84$, $p<.001$, $d=.49$). The difference between the ungrammatical and no-gesture conditions was also significant ($t(59)=2.91$, $p=.005$, $d=.38$). However, the comparison between the grammatical and ungrammatical gesture conditions did not reach statistical significance ($t(59)=1.21$, $p=.232$, $d=.16$). A similar pattern emerged for accuracy, where performance in the grammatical gesture condition was significantly higher than in the no-gesture condition ($t(59)=3.27$, $p=.002$, $d=.42$), while the contrast between the two gesture conditions remained nonsignificant ($p>.10$).

Table 3. Means and standard deviations for pairwise comparisons

Comparison	Variable	Mean Difference	t	p (Bonferroni)	Effect size
Grammatical – No Gesture	Reaction Time	46.2	3.84	<.001	0.49
Ungrammatical – No Gesture	Reaction Time	33.7	2.91	.005	0.38
Grammatical – Ungrammatical	Reaction Time	12.5	1.21	.232	0.16
Grammatical – No Gesture	Accuracy	0.04	3.27	.002	0.42
Ungrammatical – No Gesture	Accuracy	0.02	1.94	.057	0.25
Grammatical – Ungrammatical	Accuracy	0.01	0.98	.332	0.13

To examine the potential moderating role of working memory on gesture effects, a hierarchical regression analysis was conducted in which the main effect of working memory was entered in the first step and the interaction term “working memory × gesture type” entered in the second step. Results showed that working memory alone did not significantly predict reaction time ($\beta = -.12$, $p = .184$). However, the interaction term reached significance ($\beta = -.27$, $p = .018$), indicating that participants with higher working-memory capacity showed greater improvements in the grammatical gesture condition relative to those with lower working-memory capacity. For accuracy, neither working memory nor its interaction with gesture type was significant ($ps > .10$), suggesting no moderating effect in this domain.

Table 4. Hierarchical regression results for predicting performance

Predictor	β	t	p
Working Memory (Step 1)	−.12	1.35	.184
Gesture Type × Working Memory (Step 2)	−.27	2.46	.018
Working Memory (Accuracy)	.09	1.02	.309
Interaction for Accuracy	−.14	1.41	.163

Qualitative Analysis

Thematic analysis of post-experimental interviews revealed several consistent patterns. Participants frequently described non-vowelized reading as requiring "more concentration," "mental energy," and "careful attention." Many reported using specific strategies for non-vowelized texts, such as "rereading difficult words," "using context to guess vowels," and "slowing down for unfamiliar words." In contrast, vowelized texts were typically described as "easier," "faster," and "more straightforward" to read.

In the qualitative section of the research, participants' narratives indicated that the use of gesture facilitated grammatical understanding for many individuals, with several reporting that gesture helped them better retain sentence structure. Others noted that the absence of gesture increased cognitive load and created a sense of "getting lost in the sentence structure." Another group noted that gestures were helpful only when they were meaningful and interpretable. Nevertheless, some participants stated that overly complex gestures were distracting. Overall, these patterns suggest that the usefulness of gesture may vary depending on gesture type and individuals' cognitive capacities.

Table 5. Summary of themes identified in the qualitative analysis

Extracted Theme	Description
Facilitation through Gesture	Gestures helped the participant's process sentence structures more rapidly.
Reduced Cognitive Load	The presence of gesture alleviated confusion in processing complex sentences.
Importance of Gesture Meaningfulness	Gestures with clear semantic relevance were most beneficial.
Distraction from Complex Gestures	Overly complex or unnatural gestures caused attentional disruption for some participants.

Discussion

The present study examined how specific characteristics of Persian orthography—namely the elimination of short vowels and the continuous connectivity of letters—affect working memory capacity and cognitive load during reading. The findings provide convergent behavioral, subjective, and eye-tracking evidence that reading non-vowelized Persian text imposes significantly higher processing demands compared to fully vowelized text. These results align with the initial hypotheses and offer new insight into the cognitive underpinnings of reading in a deep and visually ambiguous orthographic system.

The substantial reduction in working memory span following exposure to non-vowelized texts suggests that orthographic opacity directly constrains the availability of cognitive resources required for simultaneous storage and processing. This interpretation is consistent with capacity-limited models of comprehension (Daneman & Carpenter, 1980; Just & Carpenter, 1992) and with evidence that phonological information plays a central role in the efficient encoding of written input in Semitic scripts (Abu-Rabia, 2001; Rahbari & Coltheart, 2009). When vowel information is removed, readers must rely more heavily on contextual inference, lexical guessing, and retroactive disambiguation, all of which consume working memory resources that would otherwise support higher-level integrative processes.

The convergent subjective and objective measures of cognitive load add further support to this interpretation. Participants not only reported greater mental effort during non-vowelized reading but also exhibited slower reaction times on the secondary task, consistent with the dual-task literature showing that cognitive load reduces available attentional resources (Brünken et al., 2004; Paas, 1992). The magnitude of this effect indicates that the processing of non-vowelized text draws heavily on domain-general cognitive systems, consistent with broader formulations of cognitive load theory (Sweller, 2011; Sweller et al., 2019).

Eye-tracking data provided fine-grained evidence for the mechanistic basis of these effects. Longer fixation durations, increased regressions, and shorter forward saccades during non-vowelized reading suggest more effortful lexical access, higher ambiguity resolution demands, and reduced reading fluency. These findings correspond closely with prior research showing that orthographic transparency strongly influences eye-movement behavior through its effects on phonological recoding and lexical quality (Harm & Seidenberg, 2004; Perfetti, 2007; Rayner, 2009). In particular, the elevated regression rates demonstrate that readers repeatedly revisit previous portions of the text to verify meaning, a phenomenon observed in scripts where diacritics or vowel marks play a critical disambiguating role (Abu-Rabia & Taha, 2004; Mirdehghan, 2010).

The intercorrelations among the measures strengthen the interpretation that these effects arise from a shared cognitive mechanism. The strong association between subjective cognitive load and regression count indicates that participants' meta-cognitive awareness of difficulty reflects measurable disruptions in reading flow. Likewise, the correlations between working memory span and both dual-task performance and eye-movement indices suggest that individuals with greater cognitive resources are better equipped to compensate for the challenges posed by orthographic ambiguity. This moderating function of working memory is consistent with theoretical accounts emphasizing its role in bridging bottom-up decoding and top-down comprehension processes (Baddeley, 2015; Cartwright, 2015; Follmer, 2018).

The qualitative findings add depth to the quantitative results by revealing readers' conscious strategies for managing orthographic complexity. Participants described using context-based vowel inference, rereading difficult words, slowing down, and depending more heavily on semantic cues when vowel marks were absent. These strategies map closely onto the processes predicted by computational and cognitive models of reading in quasi-regular orthographies (Frost, 2012; Plaut et al., 1996; Ziegler & Goswami, 2005). Importantly, the qualitative reports underscore the extent to which reading non-vowelized text is not simply slower or more errorprone but cognitively reconfigured, requiring continuous problem-solving and adaptive allocation of attention.

The exploratory gesture-related analyses, although outside the primary focus of the study, offer an interesting parallel. Gestures helped reduce syntactic ambiguity in a manner similar to how vowels help reduce orthographic ambiguity, suggesting that multimodal cues may serve as compensatory supports for readers processing complex or underspecified linguistic input. The moderating role of working memory in responding to gesture cues mirrors its moderating role in managing orthographic complexity, pointing toward a broader cognitive mechanism linking resource availability to disambiguation across modalities.

Taken together, these findings contribute to ongoing discussions regarding the cognitive implications of Persian orthography and other vowel-optional scripts. They support the view that eliminating vowel information substantially increases the cognitive cost of reading and that such effects are observable across perceptual, attentional, memory-based, and subjective domains. These results also have practical implications for literacy instruction, assessment design, and text presentation in digital environments, where small changes in orthographic transparency may significantly alter cognitive load.

Future research could investigate how experience, proficiency, and early literacy instruction moderate these effects, as suggested by developmental models of reading (Koda, 2005; Perfetti & Stafura, 2014). Longitudinal designs may further clarify whether repeated exposure to non-vowelized texts leads to improved efficiency or merely entrenches compensatory strategies. Neurocognitive methods such as EEG or fMRI could also help delineate the temporal and cortical dynamics underlying the additional processing demands observed here. Finally, cross-linguistic comparisons with other abjad-type scripts, such as Arabic, may illuminate shared principles and language-specific adaptations in managing vowel-optional orthographies.

Overall, the study demonstrates that Persian script complexity exerts a robust and multi-level influence on working memory capacity and cognitive load, shaping both the subjective experience and the underlying cognitive processes of reading. These insights contribute to a more comprehensive understanding of how the structure of a writing system can modulate the cognitive architecture of reading.

Conclusion

This study demonstrated that the orthographic features of the Persian script, particularly the omission of short vowels, pose a substantial cognitive challenge during reading. Skilled adult readers experience increased cognitive load and reduced functional working memory capacity when processing standard non-vowelized text compared to fully vowelized text. These findings underscore the importance of orthographic transparency in shaping reading processes and have meaningful implications for both theory and practice.

From a practical perspective, the results suggest that strategic use of vowelization, especially in early literacy instruction or with struggling readers, can reduce cognitive burden and free up cognitive resources for comprehension. The findings may also inform the design of educational materials, both digital and print, and support the assessment of reading proficiency in Persian. Theoretically, the results indicate that reading models should account for the unique demands of abjad-type scripts such as Persian, where word identification often relies more heavily on morphological and contextual analysis due to inherent phonological ambiguity.

Several limitations should be considered while generalizing the results. The sample consisted of skilled adult readers, thus, the findings may not be generalizable to children or less proficient readers. Additionally, the study focused on relatively short experimental texts, and the long-term effects of reading longer or more complex passages remain unclear. Future research could explore the long-term effects of vowelization, the moderating role of reading experience and skill level, and the influence of early literacy instruction on cognitive load. Employing neurocognitive methods could further clarify the underlying cognitive processes. Cross-linguistic comparisons with other abjad scripts could also enhance understanding of cognitive adaptations to orthographic ambiguity and inform both theoretical models and educational practices.

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Conflict of interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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