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Tarik N. Mohamed[1, 2]
[1] Department of Global Studies, Business School, KFUPM, Dhahran, Saudi Arabia
[2] Interdisciplinary Research Center for Intelligent Secure Systems (IRC-ISS), KFUPM, Dhahran, Saudi Arabia

The impact of length, rotation, and repetition in Arabic words: Event-related potential evidence

The current study investigated the effects of word length, rotation, and repetition on the early processing of Arabic words in 24 Arabic-speaking college students (M_{age} = 21.6 years, *SD* = 1.67). Using a priming repetition paradigm, participants quickly determined if prime (S1) and probe (S2) words were the same or different. Event-related potentials (ERPs) were measured, focusing on P100, N170, and N250 components. Behavioral results indicated longer response times (RTs) and higher error rates for nine-letter, rotated, and non-repeated words. ERP results for the prime (S1) showed significant effects of word length and rotation on P100 and N170 components. Specifically, nine-letter words and 90 °-rotated words elicited higher amplitudes. For the probe (S2), no effects were found on P100, but 90 °-rotated words showed higher N170 and N250 amplitudes. These findings suggest that early stages of Arabic word processing are influenced by word length and rotation. They contribute to the understanding of Arabic word recognition.

Key words: word length, word rotation, word repetition, event-related brain potentials (ERPs), N170, N250, brain activity

Address for correspondence: Tarik N. Mohamed
Department of Global Studies, King Fahd University of Petroleum & Minerals, 31261, Dhahran, Saudi Arabia
E-mail: tarik@kfupm.edu.sa

Introduction

Research in word recognition is vital as it enhances our understanding of the brain's ability to process various forms of words, including both Latin and non--Latin scripts. This field of study explains the cognitive and neural mechanisms involved in recognizing and interpreting written language, regardless of the script or linguistic system. By examining how the brain differentiates and comprehends diverse word forms, researchers can explore universal principles of language processing and identify script-specific adaptations. For instance, Latin scripts may be processed differently compared to non-Latin scripts like Arabic, Chinese, or Greek (Boudelaa, 2014; Kaltsa & Papadopoulou, 2024; Tsang & Zon, 2022), highlighting the brain's remarkable flexibility and adaptability.

Studies have shown that the brain engages distinct neural pathways and cognitive strategies depending on the complexity and familiarity of the script being processed (Choudhury & Sarma, 2023; Hershman et al, 2024). Processing a highly familiar script like Latin may involve more automatic and efficient neural mechanisms, whereas non-Latin scripts might require more effortful processing, particularly if they involve different orthographic rules or visual features (Van Soeren, 2023; Yu et al., 2023). Understanding these differences is crucial for developing comprehensive models of reading and for creating effective educational strategies for multilingual individuals.

However, despite advances in understanding word recognition across various scripts, there is still a significant gap in our knowledge regarding Arabic word recognition (Alqahtani & Alothaim, 2022; Syahid & Nurdianto, 2022). The Arabic script, with its unique features such as right-to-left orientation (Yassin et al., 2020), cursive nature, and complex morphology, presents a distinct set of challenges and opportunities for researchers (Habash, 2022; Malakar et al., 2022). Studying Arabic word recognition can provide valuable insights into how the brain manages complex scripts and help improve literacy and educational outcomes for Arabic-speaking populations.

According to the perceptual expertise hypothesis, individuals recognize words in their native language more effectively than words from other languages (Brice et al., 2023). This hypothesis posits that these words are processed in parallel, meaning that the letters within a word are recognized simultaneously. Letter information plays a crucial role in word recognition (Hendrickson et al., 2022). Consequently, expert readers are expected to employ perceptual expertise and parallel processing when encountering words in their usual form (Ventura & Cruz., 2024). However, when words are presented in unfamiliar formats, such as rotated words, serial word recognition is anticipated (Fernández-López et al., 2023).

The local combination detector (LCD) model suggests that word recognition relies on letter strings, which are fundamental elements in detecting visual words (Dehaene et al., 2005; Perea et al., 2020). This model proposes a hierarchically organized visual stream that enables the parallel processing of visual words. Specifically, the ventral visual stream combines line segments to form small local patterns, which further assemble into letters, groups of letters, and words (Flick, 2023). In contrast, when words are encountered in unfamiliar contexts, rapid parallel processing is disrupted (i.e., rotation), necessitating the engagement of auxiliary mechanisms in the dorsal pathway. These mechanisms facilitate recognition by sequentially examining each letter in a letter-by-letter manner (Ellis et al., 1987).

In addition, the sequential encoding regulated by inputs to oscillations in the letters (SERIOL) model provides further insight into word recognition by outlining a series of processing stages responsible for different aspects of letter and word processing (Whitney, 2001, 2008). According to the SERIOL model, word recognition begins with the initial visual input from the letters captured by the retina. Basic visual features of the letters, such as lines and curves, are then detected. Individual letters are identified based on these features, followed by the processing of pairs of letters (bigrams) to provide context and aid in the recognition of letter sequences. Finally, the entire word is recognized as a coherent unit. The SERIOL model emphasizes the role of oscillatory inputs in regulating this sequential encoding, ensuring that letters are processed in the correct order. This model complements the LCD model by highlighting the layered and sequential nature of letter processing, further explaining the complex mechanisms underlying word recognition.

Event-related potential (ERP) recording is extensively utilized in word recognition research. Despite its low spatial resolution, ERP offers exceptional temporal resolution, down to the millisecond. These characteristics make ERP particularly well-suited for examining the temporal dynamics of word recognition, especially when considering factors such as word length (Abdelrheem, 2021; Mohamed 2018a), rotation, and repetition (Fernández-López et al. 2023; Li et al. 2022; Mohamed, 2018b; Tsuboi et al., 2021).

ERP studies have identified different components associated with various stages of word recognition, including the P100, N170, and N250 components. The P100 is a positive ERP component that occurs between 80 to 120 milliseconds after stimulus onset, peaking at around 100 milliseconds (Sereno et al., 1998). It reflects the brain's initial response to visual stimuli, including faces (Mohamed, 2017a, 2017b), and words, indicating the processing of basic visual features such as contrast, luminance, and spatial frequency. The N170 is a negative ERP component that occurs between 120 to 200 milliseconds after stimulus onset, peaking at around 170 milliseconds (Hauk & Pulvermüller, 2004; Strijkers et al., 2010). The N170 is more pronounced for letter strings and words compared to nonlinguistic visual stimuli, supported by studies showing enhanced N170 responses to alphabetic stimuli over nonalphabetic stimuli. This suggests its crucial role in processing orthographic information (Bentin et al., 1996). The N250 component, which is influenced by word repetition, occurs between 220 to 340 milliseconds and peaks at around 250 milliseconds. The N250 is associated with the processing of visual word forms and their phonological representations. It is believed to indicate the integration of orthographic (visual) and phonological (sound) information during word recognition (Holcomb & Grainger, 2007). These ERP markers are sensitive to factors such as word length, rotation, and repetition, providing valuable insights into the temporal dynamics of word recognition (Mohamed, 2018a).

The P100 and N170 peaks have gained significant attention in the study of word recognition. For instance, Kim and Strakova (2012) demonstrated that the N170 is more responsive to letter strings than to nonlinguistic strings of similar visual complexity (Maurer et al., 2008). Lien et al. (2021) explored the influence of English word length on the word-selective N170 using ERPs to determine whether this component is affected by letter-based and word-based processing, or both. Their results indicated that the word-selective N170 exhibited a greater response to mixed-case words compared to consistently lowercase or uppercase words. This finding suggests that mixed-case words, which require access abstract grapheme representations, are processed in a letter-based manner.

Another study by New et al. (2006) re-examined the effect of English word length on lexical decisions using multiple regression analyses. Their findings revealed that the number of letters in a word had a facilitatory effect on words with three to five letters, no significant effect on words with five to eight letters, and an inhibitory effect on words with 8-13 letters.

Previous studies have yielded inconclusive findings regarding the perception and recognition of word length. Word length is typically determined using two related measures. The first is the number of letters in a word. At this stage, the word can be perceived as a whole, and recognition occurs when the letters align with the spelling of a stored word in the mental lexicon (Van Hell, 2022). The second emphasizes phonological metrics, namely, the quantification of phonemes and syllables, which serve to distinguish various components within a given word. This measure often shows substantial intercorrelations with additional variables influencing word recognition, such as the number of orthographic neighbors and printed frequency (Abdelrheem, 2021; Carlos et al., 2019; Gregg et al., 2023; Martin et al., 2012; Mohamed, 2018a).

Evidence indicates that the N170 component is influenced not only by-word length but also by word rotation (Björnström et al., 2014; Rossion et al., 2003). For instance, Fernández-López et al. (2023) examined the resilience of letter detectors in a word recognition system when letters are rotated. Their study revealed minimal difficulty at a 22.5 ° rotation angle, statistically significant difficulty at 45 °, and substantial difficulty at 67.5 °. In a related study, Fernández-López et al. (2022) conducted a masked repetition priming lexical decision experiment to investigate whether letter rotations above 40-45 ° disrupt the mapping of visual input onto orthographic representations of English words. Targets were consistently presented in the standard horizontal format, while individual letters of the identity/unrelated primes were rotated at 0 °, 45 °, or 90 °. Behavioral and ERP results indicated that the identity priming effect decreased as a function of letter rotation, supporting the notion that higher degrees of rotation impair word recognition. Li et al. (2022) investigated the influence of word rotation on the recognition of Chinese characters and its effects on neural responses. Their results showed that inverted letters led to longer response times and increased activation in the fusiform gyrus (FG) compared to upright words. Benyhe and Csibri (2021) conducted a comprehensive analysis of letter rotation effects using a masked-repeat priming technique to examine the legibility of Hungarian words presented in atypical orientations. Their findings, consistent with prior word recognition theories, showed orientation-related priming effects.

Experiment

The current experiment aimed to investigate the influence of Arabic word length, rotation, and repetition on the early stages of Arabic word recognition. Specifically, the study focused on the most prominent ERP markers associated with these stages, namely P100, N170, and N250. By examining these ERP components, the study sought to explain how these factors impact the neural processes involved in the initial recognition and processing of Arabic words. Understanding these influences can provide deeper insights into the cognitive mechanisms underlying Arabic word recognition and contribute to the broader field of psycholinguistics.

Method and Materials

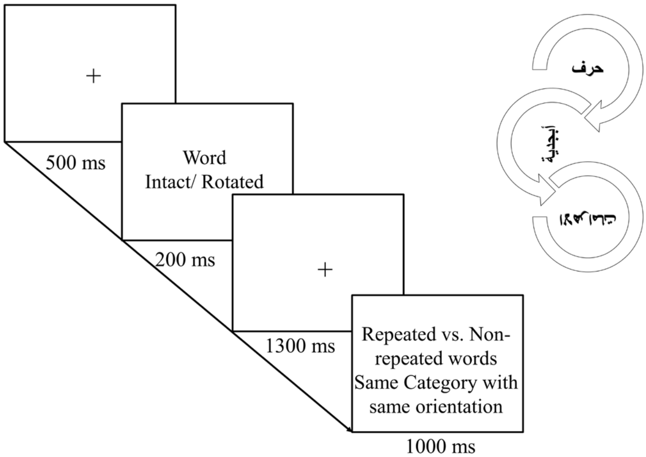
Participants

The data were collected from 24 right-handed Arabic-speaking college students, including nine females, at Sohag University in Egypt. The participants had an average age of 21.78 years (*SD* = 1.67), and all had normal or corrected-to--normal visual acuity. All participants were monolingual and provided written informed consent to participate in the study. Prior to participation, a comprehensive screening procedure ensured that none of the participants had a history of hearing or visual impairments, reading or learning challenges, or any neurological disorders that could potentially influence the study results. The current study adhered to the ethical standards outlined by the American Psychological Association (APA) for conducting research involving human subjects.

Stimuli

This study utilized 120 Arabic words selected from a database (Mohamed, 2018a). The word stimuli varied in length (i.e., 3, 6, and 9 letters), were written in black, and presented on a white background (for the full list of word stimuli used, see Appendix 1). All stimuli were rotated at four different angles: 0 °, 90 °, 180 °, and 270 ° (see Figure 1). At the end of the experiment, participants were asked to rate the frequency of the words using a Likert scale ranging from 1 (*nonfrequent*) to 5

Figure 1. *Trial Procedure. Participants Compare the Prime (S1) and Probe (S2) to Determine if They are the Same or Different.*



(*highly frequent*). The average frequency was calculated, and values were statistically compared using a one-way analysis of variance (ANOVA) across the three-word length categories. The ANOVA revealed no statistically significant differences in frequency between the word lengths, $F(2, 117) = 0.83$, $p = .64$ (Mean frequency ratings: 3-letter words = 3.63; 6-letter words = 3.72; 9-letter words = 3.80)

Procedure

Participants were seated in front of a computer monitor positioned at a consistent viewing distance of 90 cm, maintained by a chin rest. Each experimental trial began with an initial black fixation cross presented for 500 ms, followed by a prime display lasting 200 ms. This prime display contained words of varying lengths (three-letter, six-letter, and nine-letter words) and orientations (0 °, 90 °, 180 °, and 270 °). After the prime display, a blank screen was shown for 1800 ms, followed by a probe display consisting of either repeated words from the prime display or non-repeated Arabic words. This setup explored ERP repetition priming effects, following a design like that described by Mohamed (2018a). Participants were instructed to respond by pressing a button, using the left index finger for “repeated” words and the right index finger for “non-repeated” words. Emphasis was placed on both response speed and accuracy during the experiment. The experimental design incorporated three key variables—word length, word rotation, and word repetition—resulting in 24 conditions of interest. In the main experiment, 40 trials were conducted for each condition, totaling 960 trials. These trials were presented in random order, with breaks allowed after every 160 trials, approximately every 10 minutes. The entire experiment lasted approximately 60 minutes and consisted of six different blocks.

Apparatus

An electroencephalogram (EEG) with 30 electrodes, following the 10–20 standard setup, was used to capture brain activity. The scalp recordings were performed using an elastic cap, ensuring that impedance levels were consistently kept below 5 kΩ for optimal electrode performance. Each electrode was securely connected to two mastoid electrodes, with the ground electrode positioned at Cz. During offline processing, the data were re-referenced to a common average reference, and ERP epochs were assessed for a duration of 1000 ms, with a baseline of -200 ms before stimulus onset. Independent component analysis (ICA) was applied to effectively reduce artifacts arising from eye movements. The EEG signals were amplified and digitized at a sampling rate of 512 Hz using a Brain Products Brain Amp Standard Amplifier. A band-pass filter (0.5–35 Hz) was used to refine the signals. Trials displaying EEG artifacts or eye movements exceeding 50 μV were excluded from subsequent analysis. The ERPs were then recalculated with reference to the common average and digitally filtered at 30 Hz to ensure a zero-phase shift.

Data Analysis

This study investigated the impact of word length (three-letter, six-letter, and nine-letter words), rotation angles (0 °, 90 °, 180 °, and 270 °), and repetition (repeated vs. non-repeated) using repeated-measures ANOVA. The P100 component was computed within a time window of 80 to 120 ms and localized at the occipital locations (O1 and O2). The N170 component was analyzed in the lateral occipital-temporal regions, spanning 140 to 220 ms, with electrodes P7, PO7, P8, and PO8 involved in the measurement. Subsequently, the N250 component was assessed in the lateral occipital-temporal regions, covering a time window of 220 to 350 ms. These specific time segments were selected to accurately capture the peak 50 ms of each component. To address covariance heterogeneity, an epsilon correction was applied using the Huynh-Feldt method.

Results

Behavioral Results

Reaction Times

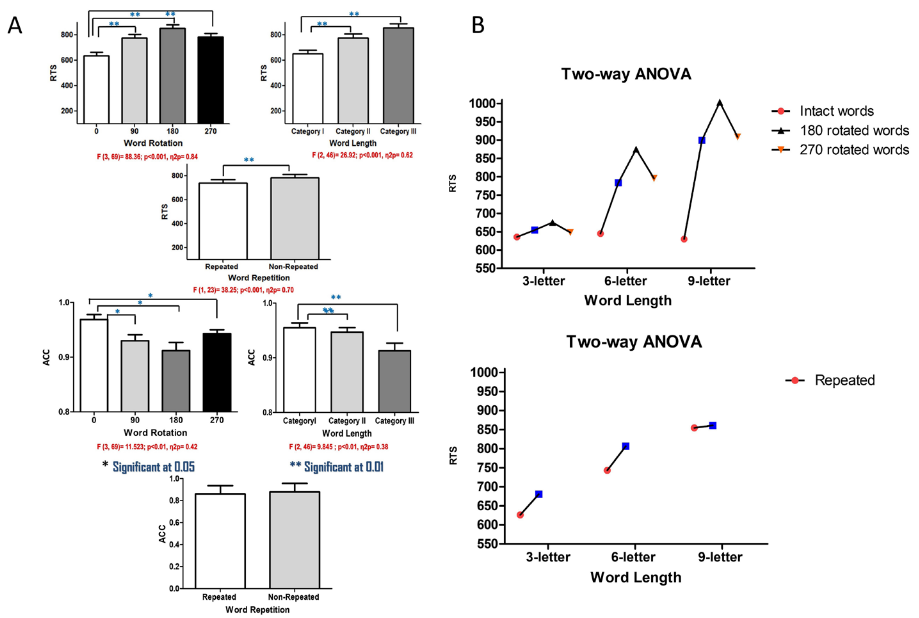
Error rates (1.4%) and responses that were faster or slower than 2 *SD*s from the mean for each participant (3.2%) were excluded from the analysis. A three-way ANOVA was conducted with within-subject factors of word length (3 levels), word rotation (4 levels), and repetition (repeated vs. non-repeated). RT results revealed a main effect of word length, $F(2, 46) = 26.92$, $p < .001$, $\eta^2_p = .62$, word rotation, $F(3, 69) = 88.36$, $p < .001$, $\eta^2_p = .84$, and word repetition, $F(1, 23) = 38.25$, $p < .0001$, $\eta^2_p = .70$. Additionally, two-way interactions were found between length and rotation, $F(6, 138) = 40.02$, $p <.001$, $\eta^2_p = .71$, and length and repetition, $F(2, 46) = 12.50$, $p < .01$, $\eta^2_p =.42$.

Post-hoc analyses for the main effect of word length revealed that both six--letter words ($p = .001$) and nine-letter words ($p = .001$) were associated with significantly RTs compared to three-letter words, with mean differences of 121.44 ms and 204.77 ms, respectively (see Figure 2). Regarding the main effect of rotation, post-hoc comparisons showed that 180 °-rotated words resulted in longer RTs ($M_{diff} = 214.482$, $p = .001$) than both 90 °-rotated words ($M_{diff} = 139.077$) and 270 °-rotated words ($M_{diff} = 147.075$; $p = .001$). No statistically significant differences were seen between 90 °-rotated words and 270 °-rotated words ($M_{diff} = 7.99$ ms, $p = .99$). Furthermore, post-hoc comparisons for the main effect of word repetition showed that repeated words had shorter RTs than nonrepeated words ($M_{diff} = 41.69$ ms, $p = .001$)

Accuracy

The analysis of accuracy included incorrect responses as well as responses that were either faster or slower than 2 *SD*s from the mean for each participant. Results indicated that main effects of length, $F(2, 46) = 9.845$, $p < .01$, $\eta^2_p = 0.68$,

Figure 2. *Behavioral Results. Panel A: Main Effects. Panel B: Interaction Effects.*



and rotation, $F(3, 69) = 11.523$, $p < .01$, $\eta^2_p = 0.42$. No other main effects or interactions were statistically significant (all *F*s < 1.1).

Post-hoc comparisons for the main effect of word length revealed that, compared to three-letter words, both six-letter ($M_{diff} = .20$; $p = .01$) and nine-letter words ($M_{diff} = .35$; $p = .01$) showed statistically significantly higher accuracy. Regarding the main effect of rotation, post-hoc comparisons indicated that error rates increased for 180 °- ($M_{diff} = .30$; $p = .05$), 90 °- ($M_{diff} = .20$; $p = .05$), and 270 °-rotated words ($M_{diff} = .21$; $p = .05$). However, no statistically significant differences were found between the error rates for 90 °- and 270 °-rotated words ($M_{diff} = .06$, $p = .83$).These results suggest that word length, rotation, and repetition each have a significant impact on word processing RTs and accuracy. Specifically, longer words (six- and nine-letter) are associated with significantly longer RTs and higher error rates compared to shorter, three-letter words. Additionally, word rotation affects both RT and error rates, with 180 ° rotations causing the most substantial increase in RTs and error rates compared to words rotated at 0 °, 90 °, or 270 °. Furthermore, repetition influences processing speed, with repeated words being processed more quickly than non-repeated words. These findings indicate that the cognitive processing of words is influenced by both the physical characteristics of the words (such as length and rotation) and their repetition, highlighting the complexity of word recognition and the multiple factors that can affect it.

Event-Related Potentials Results

Prime Data Results

Data from the first presentation of the Arabic word "Prime" were analyzed, focusing on two factors: length (three levels) and rotation (four levels). The analysis of the P100 mean amplitude (see Figure 3) revealed a main effect of word length, $F(2, 46) = 6.954$, $p < .001$, $\eta^2_p = .23$, and rotation, $F(3, 69) = 5.385$, $p < .01$, $\eta^2_p = .16$. No other main effects or interactions were observed (all *F*s < .9). The P100 peak latency analysis did not show any main effects or interactions (all *p*s > .14).

Post-hoc comparisons for the main effect of word length revealed a statistically significant difference in the P100 mean amplitude between three-letter and nine-letter words ($M_{diff} = .837$; $p = .035$), showing a larger P100 mean amplitude for nine-letter words compared to three-letter words. However, no statistically significant differences were seen between three-letter and six-letter words ($M_{diff} = .51$; $p = .11$) or between six-letter and nine-letter words ($M_{diff} = .34$; p = .33). Regarding the main effect of rotation, post-hoc comparisons showed a statistically significant difference between intact words and 90 °-rotated words ($M_{diff} = .617$; $p = .03$), reflecting a larger P100 amplitude for 90 °-rotated words than for intact words.

The analysis of N170 means amplitude revealed main effects of word length, $F(2, 46) = 7.205$, $p < .01$, $M_{diff} = .27$, and rotation, $F(3, 69) = 43.58$, $p < .001$, $M_{diff} = .65$. No other statistically significant effects or interactions were observed (see

Figure 3). For the N170, the peak latency findings did not show main effects or interactions (all ps > .20).

Post-hoc comparisons examining the main effect of word length revealed a statistically significant difference in N170 mean amplitude between three-letter and nine-letter words ($M_{diff} = -1.098$; $p = .017$). This indicates a larger N170 mean amplitude for three-letter words compared to nine-letter words. However, no statistically significant differences were observed between three-letter and six-letter words ($M_{diff} = .229$; $p = .82$). Furthermore, a statistically significant difference was observed between six-letter and nine-letter words ($M_{diff} = .869$; $p = .007$), indicating a larger mean amplitude for six-letter words compared to nine-letter words. Post-hoc comparisons for the main effect of rotation revealed statistically significant differences in the N170 mean amplitudes. Specifically, there was an increase in the N170 amplitude for 90 °-rotated words compared to intact words ($M_{diff} = 2.167$; $p = .001$). A statistically significant difference was found between intact and 180 °-rotated words, with the 180 °-rotated words exhibiting a larger N170 amplitude ($M_{diff} = 1.486$, $p = .001$). A statistically significant difference was observed between intact and 270 °-rotated words, indicating a larger N170 amplitude for the 270 ($M_{diff} = 2.405$, $p = .001$).

A statistically significant difference was observed between 90 °-rotated and 180 °-rotated words ($M_{diff} = .681$; $p = .007$), signifying a larger N170 amplitude for 90 °-rotated words. A statistically significant distinction was observed between 180 °-rotated and 270 °-rotated words ($M_{diff} =.919$; $p =.003$), revealing a larger N170 amplitude for 270°-rotated words than for 180°-rotated words.

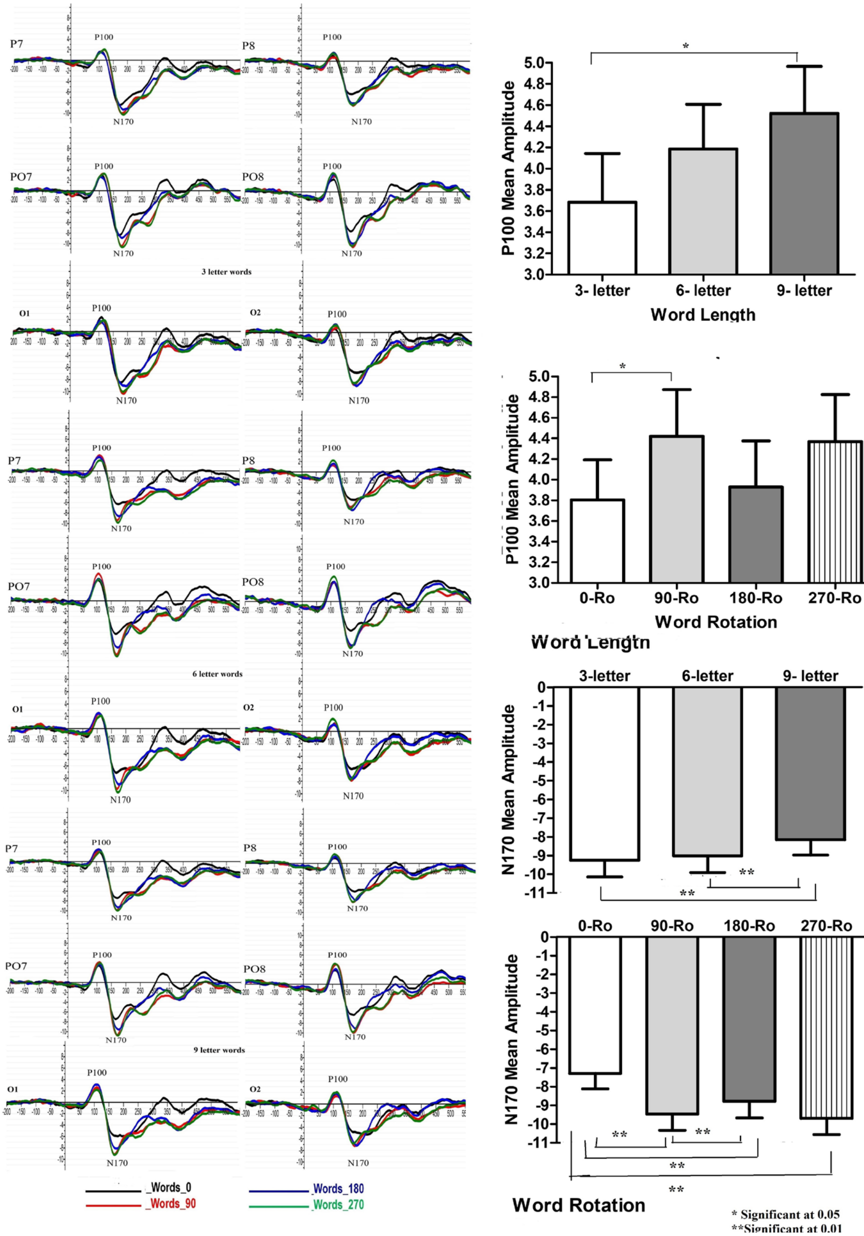
Probe Data Results

The analysis of P100 mean amplitude (see Figure 4) revealed a statistically significant effect of word rotation, $F(3, 69) = 4.365$, $p < .05$, $\eta^2_p = .21$. Furthermore, a statistically significant three-way interaction involving word length, rotation, and repetition was observed, $F(6, 138) = 2.693$, $p <.05$, $\eta^2_p = .16$. However, the analysis of P100 peak latency did not reveal any main effects or interactions (all ps > .16). Post-hoc comparisons for rotation showed no differences between intact and rotated words.

The analysis of N170 mean amplitude revealed a main effect of word length, $F(2, 46) = 4.993$, $p < .05$; $\eta^2_p = .22$. Additionally, a statistically significant effect of rotation was observed, $F(3, 69) = 22.331$, $p < .001$, $\eta^2_p = .19$ was observed. No other significant effects or interactions were found (all ps > .10).

Post-hoc comparisons examining the main effect of word length revealed a statistically significant difference in N170 mean amplitude between six-letter and nine-letter words ($M_{diff} = -0.603$; $p = .022$), with six-letter words showing a larger N170 mean amplitude compared to nine-letter words. However, no statistically significant differences were observed between three-letter and six-letter words ($M_{diff} = .178$; $p = .99$). or between three-letter and nine-letter words ($M_{diff} = -0.322$; $p = .85$).

Figure 3. *Event-Related Potentials Results for the Prime. Focus on the P100 and N170 Components.*



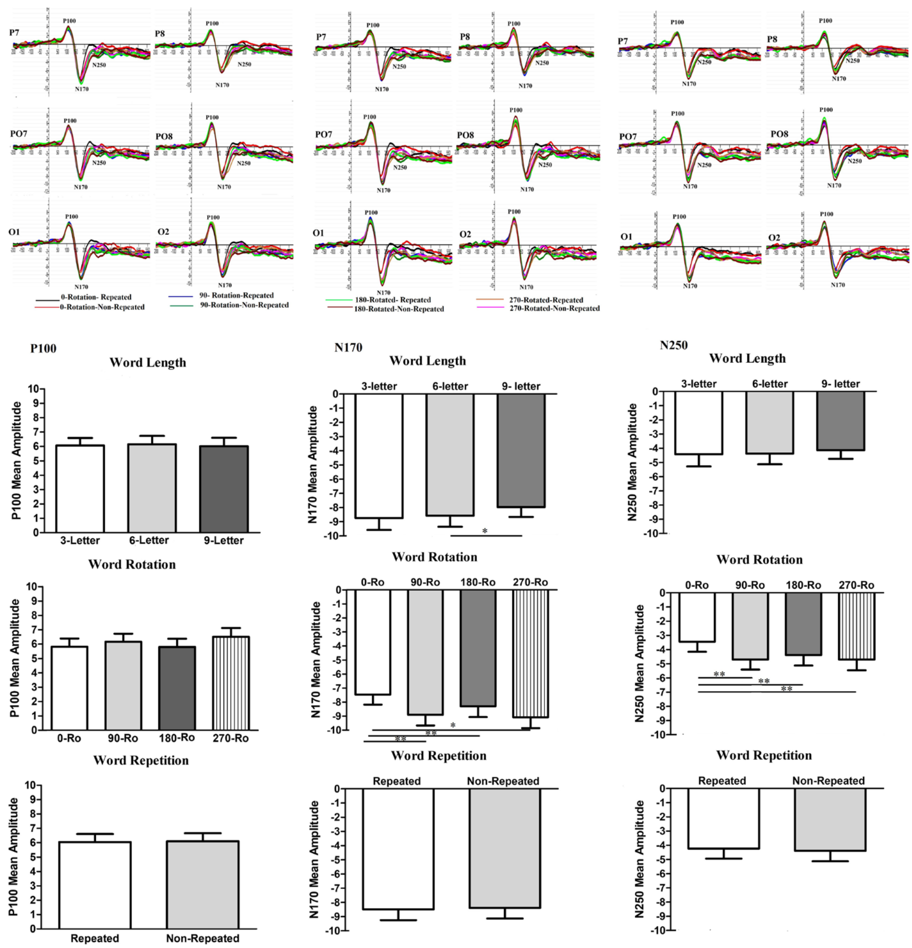
Post-hoc comparisons regarding the main effect of rotation revealed statistically significant differences in N170 mean amplitudes. Notably, there was a substantial increase in N170 amplitude for 90 °-rotated words compared to intact words (M_{diff} = 1.433; p = .001). A statistically significant difference was observed between intact words and 180 °-rotated words (M_{diff} = 1.486, p = .001), with the

180 °-rotated words showing a larger N170 amplitude (see Figure 4). A statistically significant difference was found between intact and 270 °-rotated words, with the 270 °-rotated words exhibiting a larger N170 amplitude (M_{diff} = .833, p = .026). Moreover, the results indicated a statistically significant difference between 90 °-rotated and 270 °-rotated words (M_{diff} = 1.615; p = .001), with the N170 amplitude being larger for 270 °-rotated words. Finally, a statistically significant difference was observed between 180 °-rotated and 270 °-rotated words (M_{diff} = .782; p = .039), revealing a larger N170 amplitude for 270 °-rotated words. The analysis of N170 latency did not reveal any main effects or interactions (all ps > .20).

The analysis of N250 mean amplitude revealed a statistically significant main effect of rotation, $F(3, 69) = 22.287$, $p < .001$. No other main effects or interactions were observed (all ps > .20).

Post-hoc comparisons regarding the main effect of rotation revealed statisti-

Figure 4. *Event-Related Potentials Results for the Probe. Focus on the P100;N170 and N250r Components*



cally significant differences in N250 mean amplitudes. Specifically, there was a substantial increase in N250 amplitude for 90 °-rotated words compared to intact words (M_{diff} = 1.267; p = .001). Aa statistically significant difference was found between intact words and 180 °-rotated words (M_{diff} = .948; p = .002). with the 180 °-rotated words showing a larger N250 amplitude (see Figure 4). A statistically significant difference was observed between intact words and 270 °-rotated words, indicating a larger N250 amplitude for the 270 °-rotated words (M_{diff} = 1.264, p = .001). For the N250 peak latency analysis, no main effects or interactions were observed (all ps > .10).

Discussion

The current study investigated the effect of word length, rotation, and repetition on the recognition of Arabic words using an ERP approach. ERPs were recorded during a repetition priming task that included three different word categories (three- six-, and nine-letter words). The words were presented in their normal orientation and rotated at angles of 90 °, 180 °, and 270 °. The results, as evaluated by RTs and error rates, revealed a statistically significant effect of repetition on both variables. Repeated words exhibited enhanced cognitive processing, evidenced by faster RTs and reduced error rates compared to nonrepeated words. These findings are consistent with previous studies on various visual stimuli, including faces and words (Mohamed, 2021; Mohamed, 2018; Mohamed, 2017). These results suggest that repetition significantly influences participant behavior, improving both the speed and accuracy of word recognition. Moreover, the frequency of word repetition correlated with a decrease in error rates, indicating that participants were less likely to commit errors when identifying repeated words. These results highlight the influence of repetition on cognitive processes associated with word recognition.

Moreover, behavioral results indicated that RTs for nine-letter words were significantly longer than for six- and three-letter words. This suggests that the human visual system processes shorter Arabic words more effectively through word routes, whereas longer words are processed more slowly through letter routes. These findings align with studies by Yum and Law (2021) and Lien et al. (2021), which highlighted faster processing of shorter words via the word route compared to the slower processing of longer words via the letter route. Yum and Law (2021) found that shorter words engage more efficient lexical processing pathways, while longer words necessitate more segmental processing, slowing down recognition speed. Similarly, Lien et al. (2021) demonstrated that shorter words are recognized faster because they are easier to access in the brain.

Furthermore, word rotation significantly impacted both RTs and error rates. When words were presented in a rotated orientation, participants took longer to recognize them and made more mistakes. Previous research has consistently shown that inverting words, such as rotating them by 180 °, increases the difficulty of word recognition. This is because the brain is familiar with processing words in their normal, upright orientation (Barnhart & Goldinger, 2013; Benyhe & Csibri, 2021; Bjornstrom et al., 2014). When words are rotated, the visual system must work harder to decode them, leading to slower response times and higher error rates. Benyhe and Csibri (2021) found that rotating words significantly increases both RTs and error rates. They attributed this to the disruption of holistic word processing, which is more efficient when words are presented in their normal orientation. Rotated words require the visual system to reprocess the letters and their spatial arrangement, making recognition slower. Similarly, Bjornstrom et al. (2014) demonstrated that inverted words disrupt the standard neural pathways used for word recognition. Their study showed that the brain's effort to reorient and recognize rotated words leads to longer RTs and a higher error rate. This increased difficulty reflects the additional neural resources required to interpret the altered visual input.

Electrophysiological data provided insights into the effects of word length, rotation, and repetition on temporal patterns of brain activation. The results of the “Prime” showed that the P100 mean amplitude was significantly influenced by word length. Specifically, nine-letter words displayed higher amplitudes than three-letter words, with no statistically significant difference between three-letter and six-letter words. These findings indicate that the P100 component, associated with early visual processing, is sensitive to word length, likely due to increased visual complexity or the time required to recognize longer words. This aligns with studies such as Davis et al. (2019), which noted similar effects. Davis et al. (2019) found that longer English words elicit higher P100 amplitudes due to greater visual processing demands required for their recognition. This increased demand is reflected in the early stages of visual processing, as evidenced by the P100 component. In terms of rotation, a larger P100 mean amplitude was observed for 90 °-rotated words compared to intact words, while this effect was absent for other rotations. The heightened neural response to 90 °-rotated words may reflect increased attention to visual novelty or unexpected configurations (Hauk et al., 2004).

The N170 results indicated a pronounced influence of word length on N170 mean amplitude, particularly between three-letter versus nine-letter words, and six-letter versus nine-letter words, but not between three-letter and six-letter words. This may be attributed to the specific visual load and familiarity with shorter words in Arabic orthography, as suggested by studies such as Mohamed (2018b), Abdelhadi et al. (2011), and Ibrahim et al. (2002). Mohamed (2018b) and Abdelhadi et al. (2011) observed that shorter Arabic words are processed more efficiently due to their lower visual complexity and higher frequency in the Arabic lexicon. Additionally, the current study highlights the significant impact of word rotation on N170 amplitude. Words rotated at 90 °, 180 °, and 270 ° exhibited greater N170 amplitudes than did intact words. These fluctuations in N170 amplitude across different rotation angles provide insights into the effects of orientation on word recognition processes. This aligns with findings from Carlos et al. (2019), which showed that mirror-inverted words produce increased N170 responses, reflecting the cognitive system's adaptation to atypical visual stimuli. Similarly, Kim and Strakova (2012) reported that word rotation increases N170 responses due to heightened processing demands, demonstrating that rotated words engage additional neural resources, resulting in increased N170 amplitudes.

The results of the "probe" word analysis indicated that the P100 mean amplitude was significantly influenced by word rotation, although post-hoc analysis did not reveal differences among the various rotations. This suggests that the alignment of Arabic words affects brain processing at the P100 stage, irrespective of individual pairwise distinctions. This phenomenon, observed in studies such as Dołżycka et al. (2023), highlights the complexity of visual word processing. Dołżycka et al. (2023) noted that early visual processing components like P100 are sensitive to overall word orientation, even if specific rotational differences are not detected.

The N170 mean amplitude showed a main effect of word length, particularly between six-letter and nine-letter words. This suggests that N170 amplitude is modulated by word length, with six-letter words evoking a larger N170 amplitude compared to nine-letter words. This complex relationship between word length and N170 amplitude was not observed for three-letter words, indicating specific processing demands for different word lengths (Nischal & Behrmann, 2023). Nischal and Behrmann (2023) found that medium-length words (e.g., six letters) may be processed more efficiently due to optimal engagement of visual and lexical processes, while short or long words may not benefit from the same efficiency.

Additionally, an increase in N170 amplitude for rotated words compared to intact words was observed. This is consistent with earlier findings that inverted words and faces lead to increased N170 responses (Benyhe & Csibri, 2021; Fernández-López et al., 2023; Li et al., 2022), suggesting holistic processing like face recognition (Mohamed et al., 2024; Mohamed, 2024). Fernández-López et al. (2023) observed that inverted words engage more extensive neural networks, resulting in higher N170 amplitudes. Li et al. (2022) supported this by demonstrating that faces and words share similar neural mechanisms for holistic processing, particularly when presented in atypical orientations.

Moreover, the current study showed a main effect of rotation on N250 mean amplitude, indicating that word rotation significantly impacts neural processes associated with the N250 component. This reflects the increased processing demands for recognizing and integrating rotated word forms. Proverbio et al. (2007) demonstrated that rotated words require additional neural resources, reflected in heightened N250 amplitudes, as the cognitive system adjusts to the altered visual configuration.

Conclusion

The current study examined the effects of word length, rotation, and repetition on the recognition of Arabic words, utilizing both behavioral and electrophysiological measures. The findings provide insights into the cognitive and neural mechanisms underlying word recognition in the Arabic language. Electrophysiological data revealed significant impacts of word length and rotation on ERP components P100, N170 and N250. The P100 component showed higher amplitudes for nine-letter words compared to three-letter words. Additionally, the P100 amplitude was larger for 90 °-rotated words, indicating heightened neural responses to visual novelty and unexpected configurations. N170 exhibited significant modulation by word length and rotation. The N250 component, associated with the processing of word forms, also showed increased amplitudes for rotated words, indicating that word rotation affects neural processes involved in recognizing and integrating word forms.

In summary, the current study provides comprehensive evidence that word length, rotation, and repetition significantly impact both behavioral and neural measures of word recognition. Shorter words and repeated words are processed more efficiently, while rotated words pose greater cognitive challenges. These findings have important implications for our understanding of the cognitive and neural mechanisms underlying word recognition in Arabic, highlighting the role of visual complexity, familiarity, and orientation in shaping word processing.

Conflict of Interest Disclosure

The author declared no potential conflict of interest in connection with this article's research, authorship, and/or publication.

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Research Ethics Statement

The study was committed to ethics and participant well-being. The research team followed human participant ethics guidelines. The study needed informed consent from all participants, assuring their voluntary participation. The study protocols were designed to minimize participant risk and discomfort. All critical or identifying information was protected. For questions about this work, contact the corresponding author.

Data Availability Statement

Supporting data can only be made accessible to researchers who sign a non-disclosure agreement due to confidentiality agreements.

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