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# Transposed-letter priming effects in Arabic-English bilinguals: shifting toward a default orthographic processing mode

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## Abstract

How does bilingualism affect orthographic processing across languages with different structures? This study investigates masked transposed-letter (TL) priming in Arabic-English bilinguals, comparing Arabic (a Semitic language with rigid orthography and weak TL effects) with English (an Indo-European language with flexible letter coding and strong TL effects). Using lexical decision tasks, we tested whether exposure to English enhances letter-coding flexibility in Arabic. Results showed robust TL priming in both languages, indicating that bilingual experience with English modifies Arabic orthographic processing, traditionally seen as resistant to letter transpositions. These findings suggest that bilingual orthographic processing is adaptable, with language-specific exposure reshaping letter-position encoding and enabling flexible word recognition across languages.

## 1. Introduction

Bilingualism, the daily use of more than one language, is a valuable avenue for exploring core questions regarding language processing and representation. One of the driving questions in the study of bilingualism relates to the interactions between the two (or more) languages of the bilingual (e.g., Fernandes et al., 2024; Francis, 2024; Gathercole, 2010; Schwieter, 2024). To date, there is a large body of evidence suggesting that the first language (L1) of a bilingual speaker exerts significant influence on their second language (L2) at all levels of linguistic descriptions, including phonology/phonetics (Avery & Ehrlich, 1992; Flege, 1995; Major, 1992), semantics (Altakhaineh & Zibin, 2017; Izquierdo & Collins, 2008; Jiang, 2004), syntax (Ionin et al., 2008; Shin & Christianson, 2012) and morphology (Ionin & Montrul, 2010; Lardiere, 2009). The reverse effects of L2 on L1 are also well documented and have been observed across all linguistic domains (Caramazza & Yeni-Komshian, 1974; Klassen et al., 2023; Montrul & Sánchez-Walker, 2013; Pavlenko et al., 2017; Treffers-Daller & Tidball, 2015). Indeed, as Flege and Bohn (2021) argue, cross-linguistic influences are not merely possible but inevitable, reflecting the dynamic interplay and bidirectional nature of bilingual language systems.

A much less understood issue in bilingual language processing concerns how the two languages interact at the level of processing mechanisms involved in lexical retrieval. A compelling example of this gap is how readers process transposed-letter (TL) pseudowords (e.g., jugde for judge, or caniso for casino). These TL stimuli are typically easier to recognize than pseudowords in which the same letters are replaced altogether (e.g., junpe, caviro). This advantage is clearly demonstrated in masked priming paradigms (Forster & Davis, 1984), where TL primes (e.g., jugde preceding JUDGE) lead to significantly greater facilitation in word recognition than replacement-letter primes (e.g., junpe, Perea & Lupker, 2004).

Masked priming studies in Indo-European languages using Roman script consistently reveal robust TL effects in lexical decision tasks (Acha & Perea, 2008; Adelman et al., 2014; Duñabeitia et al., 2007; Grainger et al., 2006; Perea & Lupker, 2004) and prelexical tasks like same-different matching (Duñabeitia et al., 2012; García-Orza et al., 2010; Kinoshita & Norris, 2009; Massol & Grainger, 2022). Importantly, these effects generalize to non-Indo-European scripts, including morpho-syllabic Chinese (Yang et al., 2019), abugida Hindi (Rimzhim et al., 2020), and logographic-syllabic Japanese (Perea et al., 2011), challenging script-specific accounts. This cross-linguistic consistency has prompted a shift in word recognition models, with newer frameworks, such as the Bayesian Reader (Norris, 2009), Overlap Model (Gomez et al., 2008), Spatial Coding Model (Davis & Bowers, 2006) and open bigram model (Grainger & van Heuven 2004), replacing strict serial processing with probabilistic, position-tolerant mechanisms.

Interestingly, the flexibility in letter-position coding observed in Indo-European languages, and in others like Chinese, Hindi and Japanese, has parallels in non-linguistic domains, such as object recognition, suggesting a domain-general processing mechanism for pattern recognition (Ahn & Bhanu, 2002; Hoffman & Richards, 1984; Biederman, 1987; Pentland, 1989). Both object recognition and letter processing are thought to be supported by the same brain region: the left fusiform gyrus (Dehaene et al., 2005; Dehaene & Cohen, 2011). This area originally evolved for object recognition, and part of it – commonly referred to as the Visual Word Form Area – was subsequently repurposed to process written language, suggesting that certain visual-cognitive mechanisms may be shared across domains. Thus, tolerance for spatial transpositions appears to be a default property of the visual system, generalizable across tasks and across languages.

Subsequent research, however, has suggested that this flexibility is not universal. Indeed, Semitic languages like Arabic and Hebrew, with their rich morphological structures, impose strict constraints on letter-position coding. This study investigates TL priming in Arabic-English bilinguals, testing whether bilingual exposure reveals the typical morphological rigidity of Arabic with attenuated TL effects in both languages or the positional flexibility of English with robust TL priming in both.

In the remainder of this paper, we first outline the morphological and orthographic systems of Arabic, then review TL effects in Semitic languages, analyzing how task demands, morphology and script adaptability influence this phenomenon. Finally, we examine how bilingual exposure to English might enhance orthographic flexibility in Arabic, presenting two experiments to ask whether bilingual experience increases letter-coding flexibility in Arabic readers.

## 2. Brief overview of Arabic orthography and morphology

Semitic languages use three distinct orthographic systems: abugida (consonants with inherent vowels), Latin script (alphabetic) and abjad (consonantal). Ethio-Semitic languages like Amharic and Tigrinya use abugidas, where consonants are primary but include inherent vowel notation (Daniels, 2018). In contrast, Maltese, a Semitic language heavily influenced by Romance languages, adopts the Latin script with explicit vowel representations (see Perea et al., 2012). As for Arabic and Hebrew, the writing system is an abjad, which primarily represents consonants – 28 in Arabic and 22 in Hebrew – with vowels typically indicated through optional diacritics. Each language also repurposes certain consonant letters to represent long vowels: Arabic uses three such letters, while Hebrew uses four, thus reflecting a common structural approach to vowel representation within their predominantly consonantal scripts. Beyond these shared abjad characteristics, however, Arabic exhibits distinctive complexity in its orthography. For instance, its script employs ligation, requiring letters to adopt context-dependent allographs (initial, medial and final) – as seen in the four forms of the letter 'ع' (ع, ـعـ, عـ, ـع) (Taha et al., 2013; Tibi et al., 2022). Another layer of complexity arises from diacritical dots, which disambiguate phonemes sharing the same base glyph (e.g., ج/☒/, ح /ħ/, خ /x/), a critical feature that is much less pronounced in Hebrew (Boudelaa et al., 2024; Perea et al., 2016).

Semitic languages also differ in how their morphological systems are organized: some, like Arabic and Hebrew, rely on the prototypical non-linear root and-pattern system, while others – most notably Maltese – incorporate substantial non-Semitic morphological features, primarily of Romance origin (Azzopardi & Borg, 1997; Hoberman, 1997). Arabic, our subject of study here, exemplifies a striking alignment between its orthography and its morphology. Indeed, Arabic orthography, with its ligation rules, allographic variation and dominantly consonantal letters, appears to be functionally well-adapted to its morphological system, which relies on root consonants (Boudelaa et al., 2023; Tibi et al., 2020; Tibi et al., 2022). Almost all Arabic words derive from nonlinear root-pattern structures (Boudelaa, Carreiras, et al., 2025; Boudelaa & Marslen-Wilson, 2015), where *consonantal* roots (e.g., 'ktb', *writing*) interleave with word patterns to generate semantic and syntactic diversity. For example, the root 'ktb' gives rise to various derived forms that evolve around the general meaning of *writing* (e.g., 'kAtib', *writer*, kitAb *book* and 'maktwb' *written*), and differ only by virtue of the word pattern. Importantly, the consonantal roots in Arabic occupy a densely populated lexical space such that even minor permutations of consonant order generate entirely distinct words with different meanings. For instance, the root 'sHb' signifies *pull*, but 'sbH' denotes *swimming* or *glorifying*, 'Hbs' means *confining* and 'Hsb' means *thinking, calculating* or *assuming something*, (Boudelaa et al., 2019). Thus, in Arabic, transposing root consonants almost invariably produces valid roots with divergent meanings, creating a lexical architecture in which orthographic adjacency is subordinate to root integrity. This tight interplay between orthography and morphology confers a privileged status on consonants – not only as primary carriers of semantic information but also as rigidly ordered units resistant to transposition (Boudelaa et al., 2019; Friedmann & Haddad-Hanna, 2014; Perea et al., 2010).

## 3. Transposed-letter effects in Semitic languages

TL effects, a hallmark of flexible orthographic processing (Grainger, 2018), are influenced in Semitic languages by three main factors: task demands (lexical vs. perceptual), morphological architecture (root-based vs. non-root-based) and script adaptability (abjad vs. non-abjad systems).

To begin with, consider Maltese, a Semitic language that uses the Latin script (non-abjad), features explicit vowels and exhibits hybrid Semitic–Romance morphology. In a Rapid Serial Visual Presentation task, Perea et al. (2012) found no processing costs for sentences containing words with transposed root consonants, relative to their intact counterparts. These results aligned with English-like flexibility and contrasted sharply with findings in Hebrew. This flexibility was attributed to the transparent orthography of Maltese and its reduced reliance on root-based morphology, which together could weaken the constraints typically imposed by consonantal roots.

By contrast, Hebrew, a prototypical root and word pattern (WP) language, exhibits a stark divide between native and loanwords. Native Hebrew words (e.g., 'mbrgh', *electric screwdriver*) show no TL priming when root letters are transposed (e.g., 'bgr' priming 'mbrgh'), while loanwords (e.g., 'agrtl', *vase*), which lack root-WP structure, do show sizeable TL priming (Velan & Frost, 2009, 2011), This suggests two distinct processing routes: a rigid, root-sensitive pathway for native words and a flexible, position-tolerant one for loanwords. Task demands further modulate this such that in the same–different matching task, even native Hebrew words show TL priming, revealing latent positional flexibility when lexical access is bypassed (Kinoshita et al., 2012).

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Arabic, the other major Semitic language, broadly mirrors but also extends the Hebrew results. Using masked priming with the lexical decision task, Perea et al. (2010) found no TL priming effects when root letters were transposed (e.g., عبيد 'Ebyd' *slaves* versus بعيد bEyd' *far*), but TL priming effects emerged when the transpositions preserved root order (e.g., فراغ 'frAg' *vacuum* → فارغ 'fArg' *empty*). Critically, Boudelaa et al. (2019) replicated Perea et al.'s (2010) findings in the lexical decision task with Arabic monolinguals, observing no TL priming for the same TL pairs (e.g., يعسدون 'yEsdwn' vs. يسدعون 'ysdEwn' priming يسعدون 'ysEdwn'). However, when testing the same materials in the same-different matching task, they reported robust TL priming effects modulated by allography. That is, a target like يسعدون is primed more efficiently by the non-allographic TL prime يعسدون, than by the allographic TL prime يسدعون. This dissociation between TL effects in the lexical task and the same-different matching task suggests that Arabic orthography tolerates letter-position flexibility at pre-lexical stages (i.e., same–different task) but enforces strict constraints during lexical access (i.e., lexical decision), likely to safeguard root-based semantic processing (cf. Lee et al., 2021 for similar results in Korean).

Importantly, this rigidity is not script-driven. For example, Uyghur, a Turkic language using Arabic script but lacking root-based morphology, shows clear TL priming in lexical decision (Yakup et al., 2015). This points to morphological structure – not the script itself – as the key limiting factor.

Other studies using single-letter substitutions also point to orthographic tolerance in Arabic, even when root integrity is partially compromised. Perea et al. (2014) found facilitation when a single root consonant was altered (e.g.,كتابة 'ktAbp' → كخابة 'kxAbp'), and Boudelaa et al. (2024) extended this to cases where both the root and the WP were affected. Although these are not TL priming effects in the strict sense, they suggest that Arabic orthography may accommodate a degree of positional and featural noise – particularly in tasks that downplay lexical access. This result, together with evidence of TL priming in perceptual same–different tasks, raises the question of whether such latent flexibility is amplified in Arabic-English bilinguals, whose second language relies on coarser letter-position coding.

Given that bilingual orthographic processing is shaped by cross-linguistic exposure (Cook, 2000; De Bot, 1992; Francis, 2000; Jessner, 2002; Kecskes, 1998; Kecskes & Papp, 2000; Kroll, 1993; Kroll & Stewart, 1994; Meade et al., 2022; Nan Jiang, 2000), we ask whether the inherent perceptual flexibility of Arabic – combined with sustained experience in English – might increase the tolerance of the word recognition system for letter transpositions. More specifically, we examine whether flexible letter coding, arguably a default property of the perceptual system, becomes more apparent in speakers of Arabic as a first language (L1) as a result of exposure to English as a second language (L2).

## 4. Bilingualism and the modulation of orthographic flexibility

Two recent studies have addressed the TL priming effect in bilinguals. The first is by Velan and Frost (2007), who examined the impact of TL in balanced Hebrew-English bilinguals and reported a marked asymmetry between the two languages. Specifically, these authors showed that Hebrew-English balanced bilinguals reading English materials exhibited a high tolerance for letter transpositions, demonstrating resilience typical of English readers, but when reading Hebrew native words, the same participants faced significant challenges due to the critical role of precise letter coding in identifying root morphemes. This suggests that Velan and Frost's (2007) bilinguals operated with two distinct letter-coding schemes: a strict scheme for Hebrew and a flexible one for English. Notably, the English scheme did not permeate the Hebrew one, despite the participants' high proficiency in English. These findings contrast with a recent study conducted by Meade et al. (2022), who recorded event-related potentials in a masked lexical decision task and found that bilinguals' dominant language (English) displayed greater flexibility in letter coding than their L2 (Spanish). The authors attributed this not to an inherent inflexibility in Spanish but rather to the idea that increased exposure to a language enhances position-tolerant orthographic processing within that language. This suggests that extensive reading experience enhances orthographic adaptability, making TL effects more pronounced in one's frequently used language.

This raises the question of what might be expected with Arabic-English bilinguals, who navigate between a Semitic language with a less rigid orthographic structure than Hebrew (Boudelaa et al., 2024; Perea et al., 2016) and a more flexible Indo-European language, English. Will they behave like the Hebrew-English bilinguals studied by Velan and Frost (2007), or will they instead exhibit some cross-linguistic TL effects as was the case of Meade et al.'s (2022) participants? To test these questions, we used a lexical decision task, as it best highlights the contrast between Arabic and English. In this task, Arabic monolinguals typically show no TL priming effects when root letters are transposed (e.g., Boudelaa et al., 2019; Perea et al., 2010), whereas English monolinguals generally display robust TL effects.

We hypothesized that, since flexible letter coding is a fundamental aspect of human visual perception – and given that recent research has shown that root integrity is not strictly required for lexical access in Arabic, as evidenced by one-letter-different priming effects (e.g., mftAH primed by m$tAH and mAtAH; Boudelaa et al., 2024; Perea et al., 2014), Arabic-English bilinguals may engage this default visual-perceptual mechanism, leading to TL priming effects in a lexical decision task in both Arabic and English. A further question is whether these TL priming effects in lexical decision will be modulated by allographic variation in Arabic, mirroring the modulation observed in the same–different matching task with Arabic monolinguals reported by Boudelaa et al. (2019).

## 5. Experiment 1: Lexical decision in Arabic-English bilinguals with English stimuli

Orthographic coding in L2 can be shaped by experience with an L1. Meade et al. (2022) examined English-Spanish bilinguals and found that although TL priming effects were stronger in English (L1), they were still present in Spanish (L2). The presence of TL effect in Spanish as an L2 is consistent with the idea that domain-general processing mechanisms are at play and that bilinguals may rely on inherent cognitive flexibility even when processing a less familiar orthographic system.

Yang et al. (2019) expanded on this line of research by studying Chinese-English bilinguals, whose L1 features a particularly flexible character-position coding scheme. Although their experiment did not follow a traditional TL priming design, Yang et al. (2019) used backward primes such as 'naelc' for the English target 'CLEAN' and found significant priming effects in Chinese-English bilinguals but not for Spanish-English bilinguals and English monolinguals. These results suggest that the flexible orthographic

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processing system developed for Chinese carried over into the processing of English, revealing an imprecise letter-position coding in their L2. Yang et al. (2021) examined Arabic-English bilinguals and found that they did not exhibit significant backward priming effects in English. However, because their study did not focus on standard TL priming, it remains unclear how letter-coding strategies developed in Arabic influence processing in the second language.

Arabic, while sharing certain structural similarities with Hebrew, appears to have a more flexible letter coding system. Indeed, although Arabic does not exhibit TL effects when root letters are transposed – a hallmark of its rigid morphological structure – there is compelling evidence that its orthographic system is more adaptable than previously thought (Boudelaa et al., 2019; Perea et al., 2010). First, Arabic shows TL priming when a root letter and a WP letter are transposed (Perea et al., 2010), indicating some tolerance for position variation when roots are partially involved. Second, Arabic reveals robust TL priming effects in pre-lexical tasks suggesting that the early stages of orthographic processing may support greater flexibility (Boudelaa et al., 2019). Finally, and perhaps most strikingly, Arabic demonstrates orthographic facilitation between non-word primes and word targets that differ by only a single root letter – whether they share the same word pattern (e.g., 'mfyr' priming 'mdyr') or not (e.g., 'mAyr' priming 'mdyr'), as documented by Perea et al. (2014) and Boudelaa et al. (2024), respectively.

These findings point to a far greater flexibility in orthographic coding in Arabic than in sister Semitic languages, where even minor alterations in root letters significantly disrupt recognition. Taken together, these results suggest that despite its reliance on root-based morphology, Arabic exhibits a surprising capacity for flexibility at the level of its orthographic system. This raises the strong possibility that Arabic-English bilinguals, when reading in their more flexible L2, may exhibit TL priming effects in English – driven by both, their experience with the adaptable aspects of Arabic and the inherent flexibility of English. This pattern would mirror the cross-linguistic flexibility observed by Velan and Frost (2007) in Hebrew-English bilinguals, who similarly demonstrated TL priming effects in their L2 (English).

## 6. Method

### 6.1. Participants

Sixty-four Arabic-English bilingual students (*Mean* age 22; SD = 2.31) from the United Arab Emirates University participated in the English version of the experiment. These participants were randomly assigned to this condition as part of a broader study, with a comparable group completing the experiment in Arabic. All participants reported daily use of both Modern Standard Arabic and English. Their proficiency in both languages was confirmed through a self-reported questionnaire assessing their speaking, writing and reading skills in each language. Additionally, participants' English proficiency in the current study was validated by their International English Language Testing System (IELTS) scores (IELTS, 2023). The IELTS is a standardized assessment that evaluates proficiency across listening, reading, writing and speaking skills, with scores ranging from 0 to 9, where higher scores indicate greater proficiency. Our participants achieved an average score of 6.26 (range = 5–8), reflecting a generally proficient level across the assessed domains. This study received approval from the Research Ethics Committee of the United Arab Emirates University and was conducted in accordance with the Declaration of Helsinki, including the signing of informed consent.

### 6.2. Materials

The materials for the English experiment were adapted from Lupker et al. (2008). Sixty-word targets from their Experiment 1a were used, paired with four different prime types: Identity prime, TL prime, substituted-letter (SL) prime and an unrelated Baseline prime. The target items had a mean length of 7.23 letters (range = 6–9). Word frequency was calculated using SUBTLEX-US, with a mean of 15.73 occurrences per million (range = 0.29–101.96), and frequency in the Hyperspace Analog to Language (HAL) database was 21920 (range = 878–1,26,061). The average Orthographic Levenshtein Distance (OLD20) was 2.57 (range = 1.7–3.7). To match the design of the Arabic experiment, baseline non-word primes were created. For the lexical decision task, 60 non-word targets were also created, each paired with four prime types. The average length of the non-word targets was 7.25 letters (range = 6–9). Table 1 below provides examples of the stimuli used in experiment 1, showing the word and non-word targets along with their associated primes.

We created four counterbalanced lists of materials so that each target appeared only once per list but each time in a different priming condition. Each participant received only one list consisting of a total of 120 targets.

### 6.3. Procedure

The presentation of stimuli and recording of response times were controlled using SuperLab™ 6.0 (Cedrus Corp, San Pedro). Primes were presented in lowercase and targets in uppercase. Each trial began with a forward mask (######) displayed for 500 ms in the center of the screen, followed by a prime shown for 50 ms, which was then replaced by the target. The target remained on screen until participants responded or 2 seconds had passed. Participants pressed a green-labeled key ('?') if the target was a word and a red-labeled key ('*Z*') if it was a non-word. Each session began with 20 practice trials, followed by the 120 experimental trials (60 words and 60 non-words). Bilingual examiners from the same population as the participants explained the task in English for Experiment 1 and in Arabic for Experiment 2. In both experiments participants were tested individually or in groups, depending on their availability, and received auditory feedback on their responses. Each session lasted approximately 25 minutes.

**Table 1.** Sample stimuli used in Experiment 1 (reproduced with permission from Lupker et al., 2008, transposed-letter effects: consonants, vowels and letter frequency)

| Stimuli | Word | Non-word |
|---|---|---|
| Prime | | |
| 1. Identity | proposal | batirah |
| 2. TL | prosopal | baritah |
| 3. SL | procogal | bazimah |
| 4. Baseline | mechimen | epugisp |
| Target | PROPOSAL | BATIRAH |

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**Table 2.** Mean response latencies (RT, in ms), standard errors (in parenthesis), error rates and magnitude of facilitation (priming in ms) in Experiment 1

| | Word | | Non-word | |
|---|---|---|---|---|
| Prime type | RT's | %Error | RT's | %Error |
| Identity | 726 (8.90) | 5.00 | 854 (10.99) | 14.17 |
| TL | 739 (9.24) | 4.17 | 859 (10.99) | 12.5 |
| SL | 774 (9.63) | 5.62 | 839 (10.27) | 12.5 |
| Baseline | 802 (9.17) | 6.88 | 851 (10.18) | 11.98 |
| **SL–TL (priming)** | **35*** | **1.45** | **−20*** | **0.0** |

*Note*: TL = transposed letter, SL = substituted letter, Baseline = unrelated non-word.
* $p < .05$.

## 7. Results

We analyzed correct response times (RTs) and error rates using linear mixed-effects (LME) models with crossed random effects for subjects and items (Baayen, 2008). Following Shmueli's (2010) approach, we focused on testing hypotheses through fixed effects significance rather than model prediction. Analyses were performed in R (Version 3.5.1; R Core Team, 2018) using lme4 (Bates et al., 2018) and lmerTest (Kuznetsova et al., 2017). For the English experiment, fixed effects contrasted Type of Change against the SL baseline to test TL differences. The complete dataset and analysis scripts are publicly available at: https://osf.io/s6qat/.

In the analysis of RTs, error trials were excluded, and RTs were log-transformed to meet the distributional assumptions of LME. Our data pruning procedure, based on *Q–Q* plot inspection, established cutoff points at 100 and 2,000 ms. Linear mixed-effects models with random slopes and intercepts were evaluated, and simplified if convergence or singularity issues arose. The mean correct RTs and error rates for Experiment 1 are presented in Table 2.

### 7.1. Word analyses

The data set for Experiment 1 consisted of 3,840 data points (64 participants × 60 targets). Out of these, 208 (5.42%) were errors and 25 (0.65%) outliers, leaving 3607 data points for analysis. We report the effects of the models that converged. For both this experiment and the next, full model details and fit indices – including fixed and random effects – are provided in Tables S1–S8 (Supplementary Materials), following the recommendations of Brysbaert and Stevens (2018) and Meteyard and Davies (2020).

Turning to the results for response latencies (see Supplementary Table S1 for details), the analyses revealed significant effects of both Type of Change and IELTS score. The three levels of Type of Change showed distinct patterns: Identity primes produced faster responses ($\beta = -0.065$, SE = 0.011, $t = -5.84$, $p < .001$), as did TL primes ($\beta = -0.053$, SE = 0.011, $t = -4.80$, $p < .001$), while Baseline primes showed slower responses ($\beta = 0.026$, SE = 0.011, $t = 2.31$, $p = .021$). Higher IELTS scores were associated with significantly shorter latencies ($\beta = -0.068$, SE = 0.030, $t = -2.30$, $p = .022$). Importantly, these effects were not modulated by interactions between IELTS and Type of Change (all *ps* > .272), indicating that proficiency influenced processing similarly across prime conditions.

For the error data, a logistic mixed-effects model was used to predict errors based on Type of Change and IELTS scores, with random intercepts for both subject and target. The results of this model indicate that the effects of Type of Change and IELTS on error rates did not reach statistical significance. Specifically, Identity ($\beta = -0.09$, SE = 0.23, $z = -0.42$, $p = .677$, 95% CI [−0.54, 0.35]), TL ($\beta = -0.34$, SE = 0.23, $z = -1.45$, $p = .148$, 95% CI [−0.79, 0.12]) and Baseline ($\beta = 0.25$, SE = 0.21, $z = 1.21$, $p = .228$, 95% CI [−0.16, 0.66]) conditions did not show significant differences compared to the reference category (SL). IELTS was also non-significant ($\beta = -0.46$, SE = 0.25, $z = -1.89$, $p = .058$, 95% CI [−0.94, 0.02]).

### 7.2. Non-word analyses

The non-word data of Experiment 1 consisted of 3840 data points, of which 491 (12.75%) were errors and 14 (0.35%) were outliers. A model similar to that used for word latencies was fitted to the English non-word data. The results indicate that Type of Change and IELTS significantly influenced response latencies. Specifically, the TL condition showed a significant effect ($\beta = 0.032$, SE = 0.012, $t = 2.62$, $p = .009$, 95% CI [0.008, 0.06]). IELTS was also significant ($\beta = -0.062$, SE = 0.030, $t = -2.06$, $p = .044$, 95% CI [−0.12, −0.003]). The interaction effects between IELTS and Type of Change were nonsignificant (all *ps* > .255).

As for the non-word accuracy data, we fitted a logistic mixed-effects model also similar to the one applied to the word errors. The results of this model indicate that Type of Change did not significantly influence error rates for English non-words (Identity: $\beta = 0.22$, SE = 0.18, $z = 1.24$, $p = .214$, 95% CI [−0.13, 0.56]; TL: $\beta = -0.005$, SE = 0.18, $z = -0.03$, $p = .978$, 95% CI [−0.35, 0.34]; Baseline: $\beta = -0.08$, SE = 0.18, $z = -0.44$, $p = .658$, 95% CI [−0.43, 0.27]). IELTS scores had a significant negative effect ($\beta = -0.70$, SE = 0.28, $z = -2.48$, $p = .013$, 95% CI [−1.26, −0.15]).

## 8. Discussion

The results from Experiment 1 provided clear evidence of substantial TL priming effects in English among Arabic-English bilinguals, aligning with previous research on the flexibility of English orthographic coding (Perea & Lupker, 2003; see also Kinoshita & Norris, 2009; Lupker et al., 2008). The significantly faster reaction times for the TL priming condition compared to the substitution-letter (SL) priming condition confirm the high tolerance for letter transpositions in English, driven by domain-general visual processing mechanisms that allow for spatial flexibility (Biederman, 1987; Tarr & Bülthoff, 1995). Furthermore, the finding that higher IELTS scores were associated with faster responses highlights the role of language proficiency in enhancing orthographic flexibility, which echoes findings by Meade et al. (2022), where more proficient bilinguals demonstrated greater adaptability in L2 processing.

These results raise questions about how orthographic flexibility might function in Arabic. For some time, Arabic was thought to have a rigid letter coding scheme akin to Hebrew due to its root-based morphology. This was strongly corroborated by the absence of TL priming effects when root letters are manipulated in lexical tasks (e.g., Boudelaa et al., 2019; Perea et al., 2010). However, recent studies challenge this rigidity, showing that Arabic, on the one hand, exhibits TL priming at the pre-lexical processing stages (Boudelaa et al., 2019), and on the other hand, it shows evidence of orthographic priming among prime target pairs differing by a single root letter (Boudelaa et al., 2024; Perea et al., 2014). The results from Experiment 1 raise the question of whether Arabic-English bilinguals may carry over some of the orthographic flexibility they develop in English into their orthographic processing of Arabic. We test this possibility in Experiment 2.

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## 9. Experiment 2: Lexical decision in Arabic-English bilinguals with Arabic stimuli

The present experiment is predicated on four observations: First, the results of Experiment 1 indicate that proficient Arabic-English bilinguals adopt the flexible coding system of English when processing that language (cf. Velan & Frost, 2007). This finding supports the view proposed by Meade et al. (2022) that letter-position encoding is not a fixed property of the visual–lexical system but rather a variable characteristic modulated by exposure and proficiency, such that tolerance for imprecision increases over time.

Second, Arabic – unlike its sister Semitic language Hebrew – has shown reliable orthographic priming between targets and non-word primes that differ by only one root letter (e.g., m$tAH–mftAH, mAtAH–mftAH; Boudelaa et al., 2024; Perea et al., 2016). This suggests not only that root integrity can be bypassed but also that letter-position coding may be less rigid in Arabic than in Hebrew, where altering a single root consonant disrupts lexical access (Frost et al., 2005).

Third, Arabic aligns with many other languages in showing flexible letter-position coding at the pre-lexical level. Research using the same–different matching task has shown robust TL priming modulated by allographic variation (Boudelaa et al., 2019; cf. Kinoshita et al., 2012, for Hebrew). In Arabic, letters vary in shape depending on their position – initial, medial, final or isolated – which introduces a layer of visual complexity (Khateb et al., 2014; Taha et al., 2013; Tibi et al., 2021; Tibi et al., 2022). This positional variation, or allography, may influence TL priming in Arabic, suggesting that despite visual variability, the system allows for flexible letter-position coding at early processing stages.

Fourth, tolerance for spatial transpositions appears to be a default feature of our visual perceptual system, cutting across object recognition (Biederman, 1987; Hoffman & Richards, 1984) and word recognition (Grainger et al., 2006; Perea & Lupker, 2004).

The convergence of these observations supports the view that while letter-position coding varies across languages, the underlying visual–perceptual system remains inherently tolerant of transpositions. Given that Arabic allows for some positional flexibility at the early processing stages (Boudelaa et al., 2019) and in one-letter-different priming (Boudelaa et al., 2024; Perea et al., 2014), exposure to English – a language with coarser position coding – may amplify this latent flexibility. In particular, proficient Arabic-English bilinguals, having internalized the more flexible system of English, may exhibit TL priming effects in Arabic.

To investigate this, Experiment 2 used a set of target words to examine not only whether TL priming effects occur in Arabic in a lexical decision task but also whether these potential effects are modulated by allographic changes resulting from letter transposition. Specifically, we ask whether a target (e.g., أغلقنا 'we closed') is more facilitated by a non-allographic TL non-word prime (e.g., أغقلنا) than by an allographic one (e.g., ألغقنا). Following Boudelaa et al. (2019), we define allography as a change in letter shape, as in أغلقنا- ألغقنا where the letter 'غـ' changes into ـغـ, or a change in the position of white space within the word, as in ينقذون 'they save' becoming the non-word ينذقون, where white space shifts within the word. In Boudelaa et al.'s (2019) experiments, these stimuli revealed no effects in lexical decision but a reliable TL priming effect in the same–different matching task modulated by allography. Interestingly, Yakup et al. (2015) reported a similar pattern in Uyghur, a Turkic language using the Arabic script but lacking the morphological constraints of the Semitic root, indicating that TL priming effects can emerge in Arabic script when unconstrained by dense root-based morphology, suggesting that language structure, rather than script alone, governs these effects. This supports the notion that linguistic structure, rather than script alone, governs letter-position effects.

Two outcomes are possible in this experiment: Bilinguals may extend English-like flexibility to Arabic, yielding TL priming, or adhere to root-based rigidity, blocking priming.

## 10. Method

### *10.1. Participants*

Seventy-three Arabic-English bilinguals (Mean age = 22, SD: 2.29), all students at the United Arab Emirates University and from the same population as those in Experiment 1, were randomly assigned to participate in the Arabic-language experiment. These participants reported daily use of both Modern Standard Arabic and English, demonstrating balanced bilingualism, and had normal or corrected-to-normal vision. Language proficiency was confirmed through a self-reported questionnaire assessing speaking, writing and reading skills in both languages. Additionally, their average IELTS score was 6.21 (SD = 0.91), indicating a high level of English proficiency.

### *10.2. Materials*

For this experiment, we used the materials from Boudelaa et al. (2019). These consisted of 60-word targets and 60 non-word targets. Each of these was combined with six prime types to form six priming conditions as shown in Table 3. The TL and SL were systematically root letters. The word targets averaged 6.12 letters long (range: 4–8)

**Table 3.** Sample stimuli used in Experiment 1 (reproduced with permission from Boudelaa et al., 2019, transposed letter priming effects and allographic variation in Arabic: insights from lexical decision and the same – different task)

| Stimuli | Word | Non-word |
|---|---|---|
| Prime | | |
| 1. Identity | يسعدون | انكهزت |
| | ysEdwn | Ankhzt |
| | 'be happy' | |
| 2. TL−Allog | يعسدون | انهكزت |
| | yEsdwn | Anhkzt |
| 3. TL+Allog | يسدعون | انكزهت |
| | ysdEwn | Ankzht |
| 4. SL−Allog | يشغدون | انطعزت |
| | y$gdwn | AnTEzt |
| 5. SL+Allog | يسزرون | انكلطت |
| | Yszrwn | AnklTt |
| 6. Baseline | تتناثج | يتخاقم |
| | ttnAvj | ytxAqm |
| Target | يسعدون | انكهزت |
| | 'be happy' | Ankhzt |

*Note*: TL−Allog = transposed letter without allography; TL+Allog = transposed letter with allography; SL−Allog = substituted letter without allography; SL+Allog = substituted letter with allography; Baseline = an unrelated prime.

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with an average frequency of 15.36 per million (range: 0.01–234) in the ARALEX and SUBTLEX-AR databases (Boudelaa, Carreiras, et al., 2025; Boudelaa & Marslen-Wilson, 2010). The non-word targets averaged 6.35 letters long (range: 5–8) and complied with the orthotactic constraints of the language.

Six counterbalanced experimental lists were created such that each target (word or non-word) appeared once in each list, primed by one of the six prime types.

### 10.3. Procedure

To account for the fact that Arabic lacks the upper- and lower-case distinction found in English, the prime and target stimuli were differentiated by font size to reduce visual similarity between the two stimuli and minimize low-level perceptual overlap. Specifically, priming items were presented in 28-point, while targets appeared in 58-point, both in the Traditional Arabic Regular font. Each trial began with a forward mask (######) displayed centrally for 500 ms, followed by the prime for 50 ms (Boudelaa, Carreiras, et al., 2025, Boudelaa, Perea, & Carreiras, 2025; Perea et al., 2014). The target then appeared and remained on screen until the participant responded or 2 seconds had passed. Participants were instructed to press the 'green key' for real words and the 'red key' for non-words. Each participant completed 20 practice trials, followed by 120 experimental trials (60 words, 60 non-words), with the session lasting approximately 25 minutes.

## 11. Results

For this experiment, the full data set consisted of 4380 data points (73 participants × 60 targets). Out of these we removed 83 error trials (1.89%) and 41 outliers (0.94%). Table 4 presents the average RT's, percent errors and magnitude of priming for Experiment 2.

### 11.1. Word analyses

Since we were mainly interested in the TL effects and their possible interaction with Allography and focused only on the four conditions (i.e., TL-Allog, TL+Allog, SL−Allog, SL+Allog) and fitted a full structure lmer model including random intercepts and random slopes for both subjects and target. The fixed effects included Type of Change (TL vs SL), Allography (+Allog vs. −Allog) and IELTS score meant to assess whether proficiency in English affects TL priming in Arabic. The model's intercept corresponded to Type of Change = SL, Allography = NoAllog and IELTS = 0.

The analyses revealed a significant effect of TL changes on response latency ($\beta = -0.04$, SE = 0.015, $t = -2.6$, $p = .009$, 95% CI [−0.07, −0.01]). In contrast, neither allographic variation ($p = .325$) nor IELTS proficiency scores ($p = .135$) was statistically significant. Similarly, the interaction between TL changes and allography was non-significant ($p = .741$).

To quantify the amount of evidence for TL priming effects in Arabic, we used an approximation of the BF based on the BIC to compare the model reported above with an intercept only model (Raftery, 1995). The results of this analysis revealed a BF of 5.01e +33, which provides extremely strong evidence in favor of the reported model over the intercept only model, that is, for the presence of TL priming effects in Arabic-English bilinguals.

For the accuracy data, we fitted a logistic mixed-effects model using maximum likelihood estimation with the Nelder–Mead optimizer to predict errors based on Type of Change, Allography, and IELTS, including random intercepts for both Subject and Target. As with the RT model, the intercept was set to Type of Change = SL, Allography = −Allog, and IELTS = 0. The results of the model yielded no reliable effects for TL ($p = .534$), Allograhy ($p = .434$) or IELTS scores ($p = .870$).

### 11.2. Non-word data

The non-word data consisted of 4380 data points, with 130 errors (2.97%) and 100 outliers (2.28%) removed. We focused on four conditions (TL and SL, with and without Allography) and fitted a linear mixed-effects model to predict logged reaction times (RTs) based on Type of Change, Allography and IELTS score. The results

**Table 4.** Mean response latencies (RT, in ms), standard errors (in parenthesis), error rates and magnitude of facilitation (priming in ms) in the Arabic Experiment

| | Word | | | Non-word | | |
|---|---|---|---|---|---|---|
| Prime Type | example | RTs | %Error | example | RTs | %Error |
| 1. Identity | يسعدون | 792 | 2.19 | انكهزت | 913 | 2.19 |
| | | (10.76) | | | (12.50) | |
| 2. TL−Allog | يعسدون | 790 | 1.92 | انهكزت | 932 | 3.69 |
| | | (11.35) | | | (12.63) | |
| 3. TL+Allog | يسدعون | 827 | 1.51 | انكزهت | 903 | 2.47 |
| | | (11.64) | | | (12.00) | |
| **(SL−Allog) minus (TL−Allog) (priming)** | | **37*** | **−0.41** | | **−29** | **−1.29** |
| 4. SL−Allog | يشغدون | 785 | 1.64 | انطعزت | 907 | 2.61 |
| | | (10.25) | | | (12.30) | |
| 5. SL+Allog | يسزرون | 810 | 1.10 | انكلطت | 923 | 3.29 |
| | | (11.13) | | | (13.23) | |
| 6. Baseline | تتناتج | 842 | 3.01 | يتخاقم | 897 | 3.56 |
| | | (11.11) | | | (12.04) | |
| **(SL+Allog) minus (TL+Allog) (priming)** | | **25*** | **−0.54** | | **16** | **0.68** |

*Note*: The example primes are for the word target يسعدون 'ysEdwn' (*be happy*) and the non-word target انكهزت 'Ankhzt'.
* $p < .05$.

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revealed the main effects of TL changes ($p$ = .798), allographic variation ($p$ = .848), and IELTS scores ($p$ = .382) to be statistically non-significant. However, the interaction between TL changes and allographic variation was significant ($\beta = -0.05$, SE = 0.022, $t = -2.08$, $p$ = .038, 95% CI [−0.09, −0.003]).

For the error data, the results revealed that none of the fixed effects (TL: $p$ = .599, Allography: $p$ = .926, IELTS scores: $p$ = .888) had any impact on error rates.

## 12. Discussion

In this lexical decision experiment, bilinguals showed robust TL priming effects in Arabic – using the same stimuli in which Arabic monolinguals failed to show such effects (Boudelaa et al., 2019; cf. Perea et al., 2010). It is important to note that 'monolingual' in Boudelaa et al. (2019) refers to individuals with minimal functional proficiency in other languages, whereas our bilingual cohort had advanced English proficiency and regular L2 use and exposure. Critically, the task type alone cannot explain this divergence: monolinguals showed no TL priming in lexical decision but did so in the same–different matching task (Boudelaa et al., 2019). This pattern suggests that monolinguals rely on root-based decomposition at the lexical level, whereas bilinguals – possibly influenced by exposure to English – show more flexible coding, even in a lexical decision task. These results align with the idea that bilingual experience, particularly with tolerant letter coding of English, can foster greater positional flexibility even in a language with traditionally strict orthographic constraints like Arabic (Biederman, 1987; Perea & Lupker, 2004).

The absence of allographic effects in the present experiment stands in contrast to previous findings with Arabic monolinguals (Boudelaa et al., 2019) and Uyghur readers (Yakup et al., 2015), where TL priming was modulated by letter-shape variation. This discrepancy likely reflects task differences: same – different tasks tap early, form-based processing, while lexical decision draws on more abstract orthographic representations. Thus, while allography modulates visual-form comparison, lexical access appears to operate on shape-invariant codes. In this respect, it is indicative that the non-word data showed no discernible transposition or allography effects, reinforcing the idea that the observed priming effects are lexically constrained – consistent with the view that letter position coding in lexical decision tasks emerges primarily through word-specific representations (Kinoshita & Norris, 2009).

A final observation concerns the role of L2 proficiency. In Experiment 1 (English), higher IELTS scores predicted faster responses, consistent with previous findings (Meade et al., 2022), and reflecting the fact that IELTS is a direct measure of English proficiency. In Experiment 2 (Arabic), however, no such effect emerged – unsurprisingly, since IELTS does not index proficiency in Arabic. This asymmetry underscores that while bilingual exposure to English may foster orthographic flexibility, such flexibility does not manifest uniformly across languages. Indeed, in Arabic the dense root-based morphological system limits how much positional imprecision can be tolerated. For instance, transposing the letters of the root sHb (pull) can yield multiple real roots with distinct meanings (sbH 'swim', Hsb 'think', Hbs 'imprison'). In contrast, English rarely yields lexical competitors via transposition (e.g., jugde → judge). Therefore, while bilingualism may promote orthographic flexibility, its manifestation is shaped by the morphological architecture of each language.

## 13. General discussion

The present study set out to investigate TL priming effects in Arabic-English bilinguals and assess whether the orthographic flexibility that characterizes Indo-European languages would extend to a Semitic language like Arabic that is characterized by a stricter orthographic coding scheme. We reasoned that proficient Arabic-English bilinguals are likely to show TL priming in their two languages based on four key facts. The first is that letter encoding in Arabic allows for more orthographic facilitation than Hebrew. Indeed, in Hebrew, lexical decision studies consistently show minimal orthographic priming for root-letter changes, as these disrupt morphological integrity (Deutsch et al., 1998; Frost et al., 1997, 2005; Velan & Frost, 2011) and orthographic effects emerge only in loanwords in lexical decision tasks (Velan & Frost, 2011) or in prelexical tasks (e.g., same-different matching tasks) that bypass morphological decomposition (Kinoshita et al., 2012). In contrast, Arabic exhibits greater orthographic flexibility, with priming observed at longer SOAs (Boudelaa & Marslen-Wilson, 2005), in minimal consonant substitutions (e.g., 'm$tAH'−'mftAH' and 'mAtAH'−'mftAH') (Boudelaa et al., 2024; Perea et al., 2016).

Second, Arabic, like Hebrew, also exhibits robust TL priming in a pre-lexical task (i.e., the same–different matching task), indicating that the first stages of processing in Arabic may operate on a flexible letter positioning coding (Boudelaa et al., 2019; Experiments 2 and 3). Third, previous research with bilinguals strongly suggests that letter position encoding adapts with increased language exposure and proficiency, tolerating more imprecision over time (Meade et al., 2022). Finally, tolerance for spatial transpositions is a general feature of the visual system, relevant to both object and word recognition (Biederman, 1987; Grainger et al., 2006; Hoffman & Richards, 1984; Perea & Lupker, 2004). Our results clearly bear out this prediction. Arabic-English bilinguals showed reliable TL effects in *both* languages. This reinforces the idea that proficiency in a language with a more flexible letter-coding system, namely English, influences orthographic processing in a language with a less flexible system, like Arabic, leading to increased tolerance for letter transposition and the adoption of the default object coding scheme. Indeed, although individual English proficiency did not directly modulate TL effects in Arabic, the bilinguals' divergence from Arabic monolinguals studied by Boudelaa et al. (2019), despite using the same stimuli and task, strongly suggests that sustained exposure to the orthographic flexibility of English broadly shifts processing strategies, even as the morphological constraints of Arabic continue to affect proficiency-related gradations (Perea et al., 2010).

An interesting second outcome of the current study is the lack of allographic effects in the Arabic experiment. A word target (e.g., يسعدون) is equally facilitated by a non-allographic non-word prime (e.g., يعسدون) as it is by an allographic non-word prime (e.g., يسدعون). This finding contrasts with prior research, particularly those by Boudelaa et al. (2019), who reported a significant modulation of TL priming by allographic variations in Arabic monolinguals, and Yakup et al. (2015) who observed robust TL priming effects among Uyghur speakers when ligation patterns (the ways in which letters connect) were maintained. The discrepancy with Boudelaa et al.'s (2019) findings may be attributed to differences in task demands as noted earlier. In the present study, we used a lexical decision task, requiring participants to make quick word/non-word judgments, likely based on abstract, underlying representations that do not account for positional variations in letter shapes. In contrast, Boudelaa et al. (2019) used a same-different matching task, which

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may allow for more flexible orthographic processing by relying on the overall shape of the target and benefiting from the positional information of letters (see Fernández-López et al., 2024, for dissociative effects related to top-down influences in masked priming effects across lexical decision and same–different tasks). In sum, TL priming in lexical decision reflects abstract orthographic coding that is unaffected by allography, whereas allographic modulation emerges in tasks that emphasize pre-lexical visual-form comparison (e.g., same–different matching task). This distinction explains why TL effects generalize across tasks, while allography effects remain task-specific.

Additionally, Arabic-English bilinguals are regularly exposed to the Roman alphabet in English, which encodes letters as abstract units without shape variations based on position. This experience could encourage Arabic-English bilinguals to develop a more abstract, less shape-sensitive approach to letter recognition, even when processing Arabic script. Consequently, they may become less sensitive to specific Arabic letter shapes (allographs). This abstraction aligns with findings that bilinguals tend to form unified orthographic representations across languages (Dijkstra et al., 1999) and suggests that Arabic-English bilinguals are potentially applying the Roman script's shape-invariant processing to Arabic script as well, especially in fast-paced tasks like lexical decision. Indeed, although Dijkstra et al. (1999) examined bilinguals with shared scripts, their findings highlight a broader principle: orthographic processing relies on abstract coding mechanisms (e.g., letter identity, positional encoding) that operate beyond script-specific visual forms. Much like linguistic variables that generalize across phonological systems (Berent et al., 2001), these mechanisms enable positional and identity-based coding to function independently of surface differences, allowing distinct scripts (e.g., Arabic ب vs. English B) to be processed through common structural principles. Supporting this, Wiley and Rapp (2019) demonstrated that Roman and Arabic letters, despite their visual dissimilarity, share processing dynamics shaped by complexity-distinctiveness tradeoffs. This suggests that cross-script interactions occur at the level of structural features (e.g., diacritics, line orientation) rather than holistic shapes, enabling bilinguals to form abstract orthographic codes that go well beyond script differences, an idea further reinforced by evidence of cross-script interaction in Japanese-English bilinguals (e.g., Nakayama et al., 2012).

In contrast, Uyghur speakers, whose primary language uses the Arabic script in a fully represented vowel structure and within a morphologically simple (non-root-based) system, might process Arabic script more in line with its allographic features. Because they rely on the script's visual characteristics – such as letter connection patterns (ligatures) – as consistent cues in reading, their orthographic processing is naturally tuned to allography. Therefore, TL effects in Uyghur unsurprisingly depend on these allographic features since such cues are integral to their reading system and recognition strategies.

Thus, while Arabic-English adult bilinguals likely rely on abstract representations less influenced by allography due to cross-script cognitive adaptation, Uyghur speakers show allographic modulation because they use these visual-structural cues in their primary orthographic processing. This difference underscores how bilingual exposure, proficiency and orthographic familiarity shape cognitive flexibility and attention to script-specific features.

Finally, it is worth emphasizing that while previous research with Arabic monolinguals found no evidence of TL priming effects in lexical decision tasks (Boudelaa et al., 2019; Perea et al., 2010), suggesting rigid orthographic coding in Arabic, the present study demonstrates robust TL priming effects in Arabic-English bilinguals using comparable stimuli and procedures. Although the absence of a monolingual control group limits our ability to attribute these effects solely to bilingualism, the divergence from prior monolingual findings (e.g., Boudelaa et al., 2019) aligns with growing evidence that bilingual exposure reshapes orthographic processing (Meade et al., 2022). In particular, extensive experience with English – a language characterized by flexible letter position coding – may enhance bilinguals' tolerance for positional deviations in Arabic, attenuating the influence of its traditionally stricter orthographic constraints.

## 14. Implications for theories of orthographic processing

The findings of this study have important implications for theories of orthographic processing and visual word recognition. First, our results highlight the fact that the language-specific nature of orthographic representations is not a fixed property but rather a dynamic one, likely to change as a function of exposure (cf. Rastle et al., 2011). Arabic speakers who learn English as a second language and use it on a daily basis shift their letter encoding strategies toward the default and show evidence of tolerating deviations from the canonical internal representations of words. Indeed, these speakers accept a TL-string (يعسدون or يسدعون) as an instance of the correct form يسعدون much like native English speakers find it easier to reconstruct JUDGE from the string 'jugde' (Grainger et al., 2006; Kinoshita & Norris, 2009; Norris & Kinoshita, 2008; Perea & Lupker, 2003, 2004).

These findings align with models of bilingual language processing that emphasize the dynamic interaction between two languages, where linguistic experience in one language influences cognitive processes in the other (Green & Abutalebi, 2013; Kroll & Bialystok, 2013; Meade et al., 2022). These findings suggest that Arabic-English bilinguals may gradually shift from the root-based decomposition typical of Arabic monolinguals (Boudelaa, 2018; Boudelaa et al., 2023) to greater reliance on full-form representations for word recognition. Full-form representations offer the advantage of occupying a less densely populated lexical space, making it less likely for letter transpositions to yield an existing word, in contrast to the root system, where such transpositions often produce another valid root (Boudelaa et al., 2019). The TL priming effects observed with Arabic-English bilinguals support this shift, indicating that lexical processing in this population increasingly favors full-form recognition, with reduced interference from the dense root-based neighborhood.

Our findings further suggest that orthographic processing may involve both domain-general and language-specific mechanisms. The tolerance for letter transposition observed in our Arabic-English bilinguals supports the view that letter coding flexibility may be a default feature of the visual perceptual system, which is also involved in object recognition (Biederman, 1987; Hoffman & Richards, 1984). However, in cases where lexical processing units coexist in densely populated neighborhoods, as is the case of the root in monolingual Arabic speakers, the default domain-general mechanism gives in to stricter language-specific mechanisms (Velan & Frost, 2011).

To integrate these findings within current TL priming models, Grainger's open-bigram model offers a compelling explanation (Grainger & Van Heuven, 2004). This model encodes letter positions relatively rather than absolutely, allowing flexible recognition despite positional shifts. Crucially, it represents bigrams at the level

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of abstract letter identities rather than as specific visual forms. This abstraction enables the model to focus on the sequence and relative positioning of letters without sensitivity to their visual shape, which supports consistent word recognition even if letter forms change due to contextual variations like font or script differences. For instance, the Arabic word يسعدون (‘ysEdwn’, ‘be happy’) would be encoded by 12 bigrams, including five contiguous (“عد”, “دو”, “ون”, “سع”, “يس”), four non-contiguous with one skipped letter (“عو”, “دن”, “يع”, “سد”), and three non-contiguous with two skipped letters (“عن”, “يد”, “سو”). This bigram pattern captures the word structure independently of precise letter positions, allowing both non-allographic (e.g., يعسدون) and allographic primes (e.g., يسدعون) formed by letter transpositions to activate the target word يسعدون equally, as both share 10 bigrams with the target.

On the other hand, perceptual models of letter order encoding such as the Overlap model (Gomez et al., 2008) and the Bayesian Reader model (Norris et al., 2010) suggest that spatial tolerance in letter position is a feature of broader perceptual mechanisms that operate across both linguistic and non-linguistic domains. In the Overlap model, for example, letters are encoded as probabilistic distributions spanning adjacent positions, not fixed points, allowing for similarity across position-independent letters. Thus, allographic and non-allographic primes such as يعسدون and يسعدون are both predicted to resemble the target ‘يسعدون’. Experimental implementations of the Overlap model on our Arabic stimulus set reveals comparable response probabilities for both TL-allographic primes (overlap: 0.68, SD = 0.055; response probability: 0.80, SD = 0.06) and TL+ allographic primes (overlap: 0.67, SD = 0.037; response probability: 0.80, SD = 0.056).

Recently, hybrid models, such as those proposed by Grainger (2024) and Romero-Ortells et al. (2024), have emerged that integrate orthographic and perceptual processing. These frameworks are particularly effective for Arabic-English bilinguals, where TL priming effects remain strong despite allographic changes. The hybrid model suggests that TL priming is driven by an abstract, allography-independent orthographic level, allowing bilinguals to experience consistent TL priming across different visual letter forms in each language. Consequently, letter identity and relative position are encoded in a way that is robust to visual shifts, preserving TL effects even when letter appearances vary significantly. This dual-layer processing framework accounts for the resilience of TL priming to changes in letter appearance, capturing the phenomenon more comprehensively than either purely orthographic or perceptual models alone.

## 15. Conclusions

To sum up, this study highlights the dynamic interaction between bilingualism and orthographic processing in Arabic-English bilinguals. Our findings revealed that while monolingual Arabic readers typically rely on strict letter coding to recognize root-based words (Boudelaa et al., 2019; Perea et al., 2010), Arabic-English bilinguals exhibit greater flexibility in letter position coding during word recognition, paralleling the patterns of English monolinguals. This flexibility likely stems from exposure to English, which may foster a tolerance for flexible letter order encoding. The results suggest that Arabic-English proficient adult bilinguals gradually shift toward full-form word recognition, moving away from the rigid root-based decomposition typical of Semitic languages, which is manifested by their skilled reading. Future research may explore these processes in novice readers. Overall, these insights emphasize that orthographic processing is shaped by both domain-general visual perception mechanisms and language-specific constraints, with bilingual experience driving adaptations in letter coding strategies.

**Data availability statement.** Raw data, analysis scripts, stimuli and additional details about our experiments are available at the Open Science Framework page of this project: https://osf.io/s6qat/.

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**Competing interests.** The authors declare no competing interests related to this research.

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