Orthographic Competition in Word Recognition During Development: An Eye-Tracking Visual World Experiment

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Abstract

How orthographic representations encode letter identity and letter position, and how these mechanisms develop with reading experience, remains a central issue for cognitive models of reading. The present study examines developmental changes in orthographic processing by assessing real-time lexical competition elicited by transposed-letter (TL) and substituted-letter (SL) competitors during visual spoken word recognition. Using the Visual World Paradigm, we tracked eye movements in third-grade children, fifth-grade children, and adult, all native speakers of Spanish. Orthographic processing was examined as a function of competitor type and word frequency. We adopted a confidence-interval estimation approach to characterize the magnitude and time course of competition effects, prioritizing effect estimation over null-hypothesis testing. Results showed increasing reading accuracy across development and a developmental increase in TL competition, while SL competition remained consistently weaker across groups. Word frequency modulated the magnitude and time course of competition effects, particularly in more skilled readers. This pattern supports predictions from the Multiple-Route Model, while frequency-sensitive effects are consistent with aspects of the Lexical Tuning Hypothesis. Together, these findings provide developmental constraints on cognitive theories of orthographic processing and highlight the value of eye-tracking methods for model evaluation.

Keywords: Orthographic processing; Reading development; Visual World Paradigm; Transposed-letter effects; Lexical competition; Eye tracking

Introduction

Reading is a foundational cognitive skill that supports academic achievement, access to knowledge, and participation in society. Fluent reading enables rapid access to the meaning from print and constitutes a core component of human cognition, making reading development a central topic in cognitive science and related fields (Castles et al., 2018; Rayner et al., 2001). However, learning to read is a complex and effortful process, and many children experience substantial difficulties during reading acquisition. For a significant proportion of learners, these difficulties persist over time and have long-term consequences for educational attainment and cognitive development. This underscores the importance of understanding the cognitive mechanisms that support successful reading acquisition and skilled word recognition (Share, 1995; Snowling & Hulme, 2012).

Theories of reading development converge on the idea that children initially rely on phonological decoding mechanisms that convert graphemes into phonemes, allowing them to read unfamiliar words. With increasing reading experience, children progressively develop more direct, lexical access to stored whole-word representations. Dual-route models formalize this developmental trajectory by proposing the coexistence of a non-lexical route, based on grapheme–phoneme conversion, and a lexical route that enables direct access from orthography to semantics (Coltheart et al., 2001; Grainger & Ziegler, 2011; Perry et al., 2007).

However, this framework does not fully capture the nature and development of orthographic representations themselves. Beyond phonological decoding, reading acquisition involves learning how letters are represented and positioned within words, enabling efficient discrimination between visually similar word forms. Evidence from skilled adult readers shows that word recognition is highly efficient and tolerant to disruptions in letter order. Adults can recognize words rapidly even when letter position is altered, suggesting that reading relies on flexible, global orthographic representations rather than strictly serial, letter-by-letter processing. This tolerance to letter position variability is a hallmark of skilled reading and represents a central challenge for cognitive models of visual word recognition (Grainger & Whitney, 2004; Rayner et al., 2006). Two influential theoretical accounts have been proposed to explain how orthographic processing develops: the Lexical Tuning Hypothesis and the Multiple-Route Model, which make distinct predictions

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about how letter identity and letter position are represented across reading development.

The Lexical Tuning Hypothesis proposes that early orthographic representations are initially coarse and broadly specified, becoming progressively more precise as the orthographic lexicon expands (Castles et al., 2007). According to this view, exposure to an increasing number of visually similar words drives a sharpening of orthographic representations, leading to improved discrimination between word forms. Consequently, tolerance to orthographic similarity—such as transposed-letter or substituted-letter similarity—is expected to decrease with reading development, reflecting increased lexical precision and more fine-grained encoding of letter identity and position.

In contrast, the Multiple-Route Model posits that skilled reading relies on the interaction of at least two orthographic processing routes: a fine-grained route that encodes precise letter identity and order, essential for interfacing with sublexical phonological representations, and a coarse-grained route that encodes letters in a more flexible manner and supports rapid lexical access (Grainger & Ziegler, 2011). From this perspective, reading experience is associated with greater reliance on flexible, coarse-grained orthographic coding, which facilitates fast and efficient visual word recognition under varying visual conditions.

The contrast between TL and SL competitors is theoretically informative because the two manipulations dissociate the orthographic dimensions encoded by each route. TL competitors preserve all letter identities and disrupt only letter position, thereby probing tolerance of the coarse-grained route to positional variability. SL competitors, in contrast, alter letter identity itself, a dimension encoded by both the coarse- and fine-grained routes. The two theoretical accounts therefore make distinct developmental predictions: the Lexical Tuning Hypothesis predicts that both TL and SL competition effects should attenuate with reading experience, as orthographic representations sharpen along both dimensions; the Multiple-Route Model predicts an asymmetric trajectory, in which TL effects persist or increase—reflecting growing reliance on flexible, coarse-grained coding—while SL effects remain comparatively stable or weaker.

Empirical evidence evaluating these accounts has primarily relied on masked priming and lexical decision paradigms. Developmental findings, however, have been mixed. Several cross-sectional studies report a decrease in transposed-letter effects with age, suggesting that increasing reading experience leads to more finely specified orthographic representations and reduced tolerance to letter position variability, in line with predictions from the Lexical Tuning Hypothesis (Acha & Perea, 2008; Castles et al., 2007). In contrast, other studies have reported stable or even increasing transposed-letter effects across development, indicating that sensitivity to flexible letter position coding may be maintained or strengthened with reading experience. These findings are more consistent with predictions from the Multiple-Route Model, which posits an increasing contribution of coarse-grained orthographic coding mechanisms in skilled reading (Colombo et al., 2019; Ziegler et al., 2014).

Importantly, recent longitudinal evidence has helped clarify these mixed developmental findings. Hasenäcker and Schroeder (2021) followed the same children from early to later primary school years (approximately second to fourth grade) and examined changes in orthographic processing using masked priming with identity, transposed-letter, and substituted-letter conditions. Their results showed that identity priming effects increased with age, indicating that representations of letter identity and lexical access become more precise with reading experience. In contrast, transposed-letter effects did not show a systematic developmental decrease but remained relatively stable over time, suggesting that tolerance to letter position variability is maintained across this period. This pattern indicates that increasing orthographic precision does not come at the expense of flexible letter position coding. Instead, the findings support an integrative view in which multiple orthographic coding mechanisms develop in parallel and jointly contribute to skilled word recognition, combining key aspects of the Lexical Tuning Hypothesis and the Multiple-Route Model.

In this context, online measures of visual word recognition offer a valuable methodological complement to traditional behavioral paradigms. Eye-tracking techniques allow the continuous assessment of processing dynamics in real time, providing insight into how lexical representations are activated and compete during visual word recognition. In particular, the Visual World Paradigm (VWP) makes it possible to examine moment-to-moment lexical competition by tracking readers' gaze to visually presented word candidates as the target word unfolds. By explicitly including competitor words that overlap with the target in orthographic features, the VWP can reveal graded activation patterns and competition effects that may not be detectable in offline or end-point measures such as lexical decision or masked priming. By comparing the activation of transposed-letter and substituted-letter competitors, the VWP provides a direct way to test the Multiple-Route Model by assessing the relative contribution of flexible, coarse-grained and precise, fine-grained orthographic coding routes across the time course of visual word recognition. Higher-frequency words, by virtue of more frequent encounters, are assumed to have more entrenched lexical representations, providing a strong test case for lexical tuning: if precision sharpens with experience, the effect should appear earliest and most clearly for high-frequency items.

Moreover, manipulating word frequency within the VWP allows predictions of the Lexical Tuning Hypothesis to be tested, as reduced transposed-letter effects for higher-frequency words would indicate that more robust mental word representations support more precise orthographic processing with reading experience.

The present study

The present study uses the Visual World Paradigm to examine developmental changes in orthographic competition during visual spoken word recognition in Spanish. By comparing transposed-letter and substituted-letter competitors across third graders, fifth graders, and adults, we aim to test contrasting predictions derived from the Multiple-Route Model and the Lexical Tuning Hypothesis. This approach provides time-resolved evidence on how orthographic representations are organized and how they change with reading experience, offering novel constraints for cognitive models of reading development.

Method

Participants Three groups participated in the study: third-grade children, fifth-grade children, and adult readers. The third-grade group consisted of 29 children (7–8 years old; 16 girls), and the fifth-grade group included 29 children (approximately 10–11 years old; 16 girls). The adult group comprised 20 participants (20–25 years old; 12 women). All participants were monolingual native speakers of Chilean Spanish, had normal or corrected-to-normal vision, and reported no history of language, hearing, or learning disorders. Child participants were recruited from schools serving a lower-middle socioeconomic status (SES) population, and adult participants were recruited from the university community. Informed consent was obtained from all adult participants and from the parents or legal guardians of child participants, in addition to their verbal assent.

Materials The stimulus set consisted of 48 Spanish target words, including 24 high-frequency and 24 low-frequency items. Each target word was paired with two types of orthographic competitors: a transposed-letter (TL) competitor created by transposing two internal letters of the target, and a substituted-letter (SL) competitor created by replacing one letter with a different one that was not contained in the target. Competitors were matched in length and general orthographic structure. Visual displays included the target, two competitors (one TL and one SL), and an unrelated distractor.

Figure 1. A representative four-item visual display as seen by the participant on a monitor. The display features the target word (*ALIMENTOS*) along with three other items: a transposed-letter (TL) competitor (*AMILENTOS*), a substituted-letter (SL) competitor (*ALICENTOS*), and an unrelated distractor (*ICOJARDAR*).

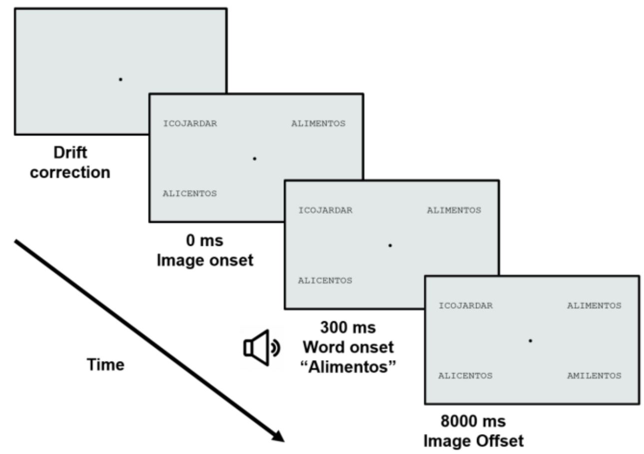

Figure 2. Schematic representation of a trial. Each trial begins with a drift correction, followed by the onset of the visual display at 0 ms. The target word (e.g., "Alimentos") is presented audibly through headphones at 300 ms. The visual display, which includes the target and the orthographic competitors and the unrelated distractor, remains on the screen until 8000 ms (Image Offset).

Design and Procedure Participants completed a Visual World Paradigm task designed to assess real-time orthographic competition during visual spoken word recognition. They were seated approximately 60 cm from the screen. Before the experimental task began, a five-point eye-tracker calibration was performed to ensure accurate recording of gaze position. Each trial started with a drift correction, followed by the onset of the visual display (0 ms). After 300 ms, the auditory target word was presented through headphones. Participants were instructed to explore the visual context (with written words), while their eye movements were continuously recorded. The total duration of each trial was 8000 ms, allowing sufficient time to capture the full-time course of lexical activation and competition. The experiment manipulated Competitor Type (TL vs. SL), Word Frequency (high vs. low), and Group (third grade, fifth grade, adults).

Data Analysis Four interest areas were defined using Experiment Builder (SR Research) to match the location and size of the four items presented on the display. We used Data Viewer (SR Research) to generate a summary of participants' fixations, including their durations and spatial coordinates. Fixation proportions were subsequently calculated by isolating all fixations directed toward the target, the competitors and the unrelated distractor.

These proportions were time-locked to the onset of the spoken word. For every millisecond of each trial, a value of 1 was assigned to the area of interest (AOI) being fixated by the participant, while all other AOIs were assigned a value of

0. In instances where no fixation was detected by the eye tracker, all regions were given a 0 value. We calculated the proportion of fixations (i.e., the percentage of fixations to a specific object across trials) per participant and experimental condition for the four areas of interest. These data were then aggregated by item, participant, and condition, and further binned into 50 ms time windows. The first level of aggregation allowed for the calculation of confidence intervals (by participants), which were corrected for within-subject designs (Cousineau & O'Brien, 2014) and multiple comparisons (Hsu, 1996). The 50 ms aggregation was implemented to reduce auto-correlation between fixation proportions over time.

To evaluate the competition effects on each age group, we adopted a statistical approach focused on quantifiable differences in fixation proportions and the time course of prediction effects, rather than a null hypothesis testing approach (Cumming, 2014; Cumming & Finch, 2005; Huettig & Guerra, 2019; Huettig & Janse, 2016). This confidence interval approach provides a continuous, detailed graphical description of the gaze patterns for each experimental condition every 50 ms. Consequently, the results can be interpreted based on the exact timing of fixations toward the target, as well as the magnitude and reliability of the observed effects (see Figures 3 and 4).

Results

As can be seen in Figure 3, adult readers show a rapid and robust orientation toward the target, reaching fixation proportions exceeding 0.80 by 2500 ms. Crucially, the competition dynamics reveal a clear hierarchy of lexical activation. The TL competitor (orange line) elicited a distinct rise in fixations, peaking between 500 and 1000 ms. The CIs for the TL condition clearly diverge from both the unrelated distractor baseline (red line) and the SL condition (green line) shortly after word onset. While SL competitors also attracted more fixations than unrelated distractors, the magnitude of the TL effect was substantially larger. The lack of overlap between the TL and SL confidence intervals during the early time window (approx. 400–1200 ms) provides evidence that skilled readers activate candidates with flexible letter positions significantly more strongly than candidates with letter substitutions.

Fifth-grade children exhibited a pattern that appears transitional between novice and skilled reading. Target fixation proportions rose more gradually than in adults, reaching approximately 0.40 by the end of the trial window. Regarding competition effects, 5th graders showed a reliable separation between competitors and distractor. Notably, the TL condition consistently trended higher than the SL condition. By the 1000 ms mark, the CIs for the TL competitor begin to diverge from the SL competitor, indicating that for these intermediate readers, misordered letters (transpositions) are becoming stronger perceptual decoys than replaced letters (substitutions). However, this separation is less pronounced and occurs later in the time course compared to adults.

Third-grade children displayed the slowest time course of recognition, with target fixations rising gradually and remaining below 0.35. The competition pattern here differs qualitatively from the older groups. While both TL and SL competitors attracted more fixations than the unrelated distractor (indicating successful lexical activation of orthographic representations), the CIs for the TL and SL conditions overlapped substantially throughout almost the entire trial. This overlap suggests that, for younger readers, a word with transposed letters and a word with a substituted letter generate roughly equivalent levels of lexical confusion. The specific "boost" in activation for transposed letters—characteristic of flexible coding mechanisms in skilled readers—is not yet statistically distinct from standard orthographic overlap in this age group.

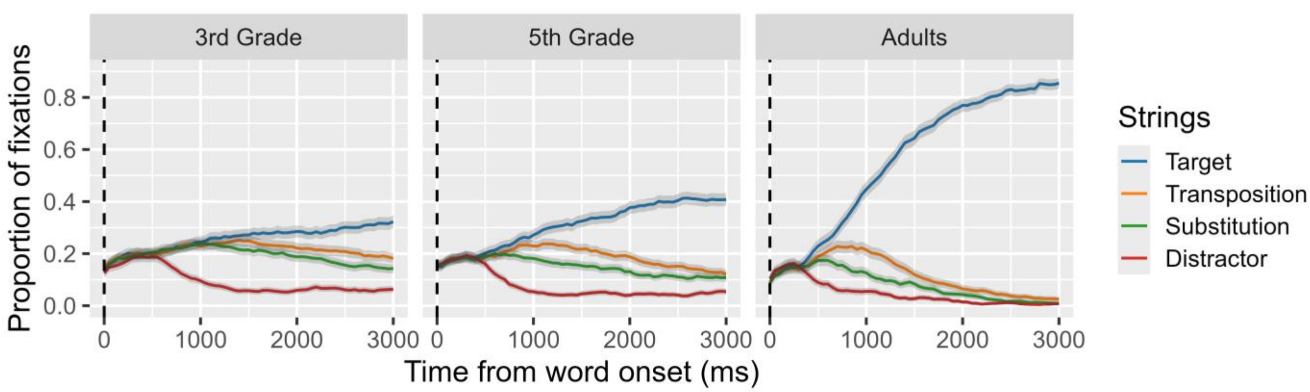

Figure 3. Mean proportion of fixations over time to the target (blue), transposed-letter competitor (orange), substituted-letter competitor (green), and unrelated distractors (red) for third-grade children, fifth-grade children, and adult readers. The dashed vertical line indicates auditory target word onset. Transposed-letter competitors elicited greater competition than substituted-letter competitors across groups, with this effect increasing with reading level, reflecting greater reliance on flexible orthographic representations in more skilled readers.

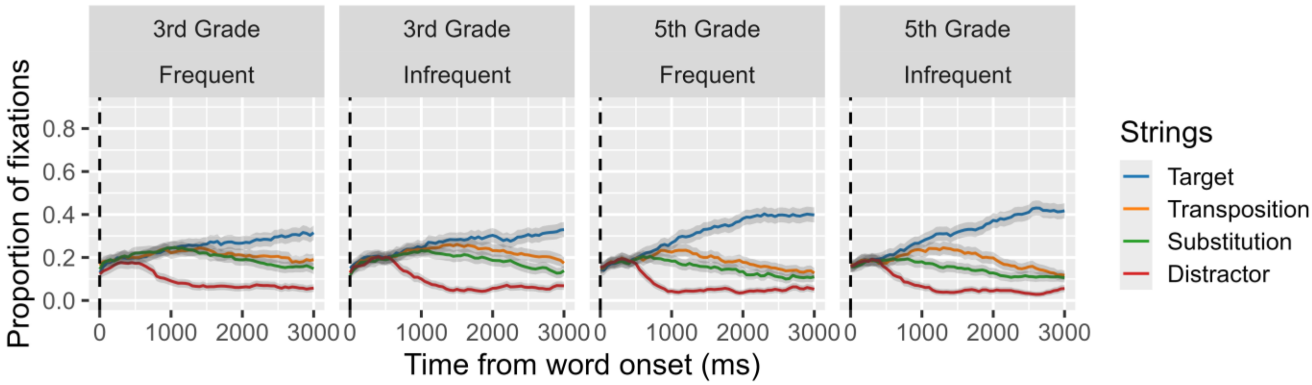

Figure 4. Mean fixation proportions over time for third-grade children and fifth-grade children, subdivided by word frequency (Frequent vs. Infrequent). The graphs tra|ck gaze directed at the target (blue), transposition competitors (orange), substitution competitors (green), and distractors (red). Word frequency is shown to modulate the magnitude and time course of competition, particularly in fifth graders, reflecting increased lexical precision as reading experience accumulates.

To investigate whether lexical precision is modulated by exposure, we analyzed the interaction between grade level and word frequency (High vs. Low) for the child groups (see Figure 4).

Fifth Graders Frequency exerted a modulatory effect on the competition dynamics in 5th graders. In the High Frequency condition, the fixation patterns closely resembled the adult profile: there is a clearer and earlier divergence where the TL competitor (orange) separates from the SL competitor (green). The CIs indicate that for well-known words, 5th graders possess a more "tuned" lexicon where letter position flexibility is active but distinct from substitution errors. Conversely, in the Low Frequency condition, the pattern is that of a more novice reader; the CIs for TL and SL competitors overlap significantly, resembling the undifferentiated competition seen in 3rd graders. This suggests that the "adult-like" processing of letter position is emergent in 5th grade and is specific to words with robust lexical representations.

Third Graders In contrast, 3rd graders showed less sensitivity to word frequency regarding the *relative* strength of competitors. Whether for High or Low frequency items, the TL and SL curves remained closely clustered with overlapping CIs. While high frequency targets were fixed slightly earlier, the competition mechanism itself—specifically the distinction between letter position and letter identity—appears largely immature across the board, regardless of item frequency.

Discussion

The present study examined developmental changes in orthographic competition during visual spoken word recognition using the Visual World Paradigm (VWP), a method that provides continuous, time-sensitive measures of lexical activation and has proven sensitive to fine-grained differences in lexical competition (Tanenhaus et al., 1995; Allopenna et al., 1998). Two main findings emerged. First, transposed-letter (TL) competition increased with reading level, whereas substituted-letter (SL) competition remained consistently weaker across groups. This pattern indicates an increasing reliance on flexible orthographic representations as reading experience accumulates. Second, word frequency modulated both the magnitude and time course of competition effects, particularly in fifth-grade readers, suggesting increasing lexical precision for well-established word forms. Together, these findings provide important evidence for cognitive models of orthographic processing and reading development.

From the perspective of the Multiple-Route Model, the observed developmental increase in TL competition is consistent with the proposal that skilled reading increasingly relies on coarse-grained orthographic decoding (Colombo et al., 2019; Grainger & Ziegler, 2011; Ziegler et al., 2014). Such representations allow readers to efficiently activate lexical candidates despite variability in letter position, facilitating robust word recognition under suboptimal or noisy conditions.

At the same time, the modulation of competition effects by word frequency—most clearly observed in fifth-grade readers—points to concurrent changes in the precision of lexical representations. High-frequency words elicited reduced TL competition and faster resolution of lexical competition, suggesting that repeated exposure leads to more finely specified orthographic representations that support more efficient discrimination among close neighbors. This pattern aligns with the Lexical Tuning Hypothesis, which proposes that growth of the orthographic lexicon necessitates increasing representational precision to minimize lexical ambiguity (Acha & Perea, 2008; Castles et al., 2007).

Taken together, these results support a hybrid view of orthographic development in which coarse-grained and fine-grained orthographic processes coexist and are dynamically weighted across development. Rather than favoring a single theoretical account, the data suggests that reading development involves changes in the relative contribution of multiple representational routes within a unified cognitive system. Flexible letter-position coding provides efficient access to lexical candidates, while increasing lexical precision refines competition resolution as experience accumulates. This dynamic reweighting offers a principled way of reconciling predictions from the Multiple-Route Model and the Lexical Tuning Hypothesis, as well as explaining previously mixed developmental findings in the literature.

The present findings also have broader implications for cognitive theories of reading and orthographic representation. Cognitive models that aim to capture skilled reading must therefore accommodate both robustness to orthographic variability and increasing lexical differentiation as joint outcomes of learning. More broadly, these results underscore the importance of integrating developmental evidence into cognitive models that are typically evaluated using adult data. Developmental trajectories provide critical constraints on architecture and learning mechanisms assumed by such models and should play a central role in theory building within cognitive science.

Several limitations should be noted. First, conclusions are based on confidence-interval estimation rather than null-hypothesis significance testing; while this approach is well suited to characterizing the magnitude and time course of competition effects (Cumming, 2014), cluster-based permutation analysis or gamm-based onset can strengthen our interpretations of findings. Second, adult and child groups were drawn from different populations (university community vs. lower-middle SES schools), and developmental comparisons should be interpreted in light of this sampling difference. Third, independent measure of vocabulary and phonological awareness were administered, and we will include them in future analysis to relate competition dynamics to individual differences. Finally, the free-viewing instruction, while consistent with prior VWP work (Huettig & Guerra, 2019), did not require an overt response, which may have contributed to lower target fixation proportions in younger participants.

Beyond these limitations, the use of eye-tracking within the VWP allowed us to move beyond end-point measures such as reaction times, which can obscure developmental differences due to global changes in processing speed. By capturing the real-time dynamics of lexical competition, the VWP provides a powerful methodological tool for testing cognitively and computationally explicit predictions about the time course of lexical activation. This fine-grained temporal perspective is especially valuable for distinguishing between competing theoretical accounts that make similar predictions at the level of final behavioral outcomes but diverge in their assumptions about processing dynamics.

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