Age-Related Differences in Processing Unconventional Text Formats

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ABSTRACT

Typographic formats influence reading efficiency; however, knowledge remains limited regarding how these effects change across the lifespan, especially for orthographic distortions in digital environments. This study examines how conventional formats (lowercase and uppercase) and unconventional formats (mixed-case and LEET) affect reading times and the integration of meaning while reading five-word phrases. Three hundred and three adults (18–84 years) read short sentences (five words) presented in the four formats, while reading times and memory accuracy were recorded. The results showed a graded cost pattern: conventional formats yielded the fastest reading times, mixed-case imposed moderate costs, and LEET produced the greatest slowdown and a slight reduction in accuracy. Moreover, a significant interaction between format and age was observed: although reading slowed with age in all formats, this effect was especially pronounced for LEET. These findings suggest that extreme orthographic distortions increase perceptual and pre-lexical demands, revealing limits in reading adaptation associated with aging.

Keywords: Typographic formats; Reading efficiency; Orthographic distortions; LEET; Lifespan; Sentence reading

Introduction

Studies in visual word recognition investigate how readers perceive, identify, and decode printed words, from the extraction of visual features through letter recognition to accessing meaning and pronunciation within the language system (Snowling, Hulme & Nation, 2022). This line of research aims to clarify the stepwise mechanisms underlying reading and written language comprehension, with an emphasis on how orthographic information activates linguistic representations. Among the multiple variables that modulate the reading process, recent literature has established that the physical properties of written words and their constituent letters (e.g., spacing, font width, orthographic format) influence the early stages of visual word recognition (Minakata & Beier, 2021; Scaltritti et al., 2019; Staub, 2020).

A particularly robust demonstration of orthographic format effects is the lowercase superiority effect, whereby, compared to words in uppercase, words in lowercase yield shorter response times and shorter fixation times (Tinker and Paterson, 1928; see also Perea, Fernández-López & Marcet, 2020; Perea, Rosa & Marcet, 2017). Two complementary explanations have been proposed for the lowercase superiority effect. First, greater exposure to lowercase text compared to all-uppercase—used mainly for titles and acronyms—establishes it as the perceptual default (Perea et al., 2017). Second, lowercase letters feature distinctive ascenders ("k", "d") and descenders ("j", "g") that create unique visual shapes absent in uniform-height uppercase letters (Paterson and Tinker, 1940).

From a developmental perspective, letter case sensitivity emerges gradually as children acquire alphabet knowledge and begin formal reading instruction. Early in literacy acquisition, children typically learn to recognize and name uppercase letters first, with accurate lowercase recognition lagging behind and improving as reading experience increases (e.g., van de Walle de Ghelcke et al., 2021). At these early stages, children often show a preference for one case over the other, but this preference quickly gives way to an abstract notion of letter identity that generalizes across visual forms (Grainger et al., 2008; Grainger, 2022). As this abstract letter identity becomes established, case information is relegated to a secondary role and the reader develops the ability to identify letters efficiently regardless of whether they appear in uppercase or lowercase.

In adult readers, case effects become much smaller but do not disappear entirely, with behavioural studies showing a subtle yet reliable advantage for lowercase words and word sequences in accuracy and/or speed (e.g., Perea & Rosa, 2002; Vergara-Martínez et al., 2020). Recent work shows that the lowercase advantage reflects more efficient early visuo-orthographic processing and case-independent letter access (Fournet et al., 2022).

However, some formats disrupt letter-shape familiarity even more strongly than uniform uppercase, because they alter not only letter size but also the internal pattern of cases within a word. Among these, the alternation of uppercase and lowercase letters within a word, namely, mixed-case, e.g.,'LOTTERY' spelled as 'LoTtErY' (Mayall et al., 1997) represents a paradigmatic example. This alternation occurs naturally in many languages, as in proper names or sentence beginnings, and, in some languages, common nouns, but it does not occur in multiple instances within a string.

Perea et al. (2015) provided a seminal analysis of mixed-case processing, demonstrating that this format disrupts word recognition by impairing letter grouping and case uniformity. Although subsequent studies remain limited, the existing evidence consistently shows that mixed-case imposes greater processing demands than conventional formats, slowing reading and hindering efficient word recognition (Mayall et al., 2001; McClelland, 1977; Poulton, 1969). This format particularly disrupts orthographic processing except for proper names, where the initial capital can facilitate recognition (Peressotti et al., 2003). This disruption has been said to arise from breaking case uniformity and impairing letter grouping due to varying heights (Arditi & Cho, 2007; Mayall et al., 1997; Mayall & Humphreys, 1996).

While mixed-case alternations constitute a clear deviation from conventional word forms, they still preserve the original orthographic identity of each letter. Other forms of visual distortion go a step further by systematically replacing one element in the written word with another —either due to strong physical overlap between characters (e.g., o–O) or phonological similarity (e.g., φ–f, which map onto /f/)— thus altering the graphical identity of the written word more radically. A clear example is Greeklish, which can be considered a form of transliteration, although it often lacks a fixed one-to-one correspondence between source and target characters. In Greeklish, Greek words are written using Latin characters that are phonologically similar to the original letters (e.g., Greek λοταρία 'lottery' rendered as *lotaría* or *lotaria*). This informal way of writing emerged in digital communication as a practical solution to software and hardware limitations on Greek-script input, and it remains frequent in online and messaging contexts (Chalamandaris et al., 2006). In this case, the alphabet changes, but phonological similarity between characters supports word recognition (Dimitropoulou et al., 2011). While Greeklish primarily reflects a functional adaptation to technological constraints, other formats, such as LEET, employ similar substitution principles for strategic purposes, including bypassing content moderation filters on digital platforms.

LEET (or L33T) represents a more extreme case within digital environments: letters are replaced by orthographically similar digits or symbols (e.g.,' lottery' → '*L0TT3RY*'; Perea et al., 2008; Grabbe, 2016). This substitution adds another layer of complexity to reading comprehension, as LEET disrupts word recognition by altering the letters rather than their format, thereby challenging the abstract letter identity tolerance that normally facilitates efficient word processing (Fournet et al., 2022). The users of platforms like Twitch and online games utilize LEET as a strategy to bypass moderation filters and to avoid the detection of censoring systems in online platforms, exploiting the fact that human readers can still recover the intended word while early filtering systems could not (Märtens, et al., 2015).

Given its peculiar orthographic characteristics, LEET has attracted attention in experimental studies exploring how altered visual word forms are processed during reading. For example, Perea et al. (2008) showed in a masked priming lexical decision task that visually similar LEET primes (e.g., L0TT3RY–LOTTERY) produce priming effects comparable to identity primes (e.g., LOTTERY–LOTTERY), relative to control primes (e.g., L6TT2R7–LOTTERY). These findings suggest that the digit-to-letter conversion process in LEET depends on significant visual resemblance between the digit and the letter it substitutes. This resemblance allows digits to function as letter instances and activate lexical representations (Carreiras, Duñabeitia & Perea, 2007; Kinoshita et al., 2014; Perea et al., 2008), likely because readers are used to assimilating letter identities across a variety of fonts and handwriting styles (see Manso de Zuniga et al., 1991). As argued by Molinaro et al. (2010), when embedded in letter strings, visually similar digits are readily regularized and encoded in a letter-like manner, whereas the reverse process (letters embedded in digit strings) does not occur to the same extent, indicating an asymmetry between letter and digit processing systems.

Building on these perceptual mechanisms, it is also important to consider characteristics of the reader that may modulate how such formats are processed. Beyond these perceptual constraints, an understudied factor in the current literature on LEET and mixed-case, and even standard case formats, is the modulatory role of age. There are at least two ways in which age and age-related factors might be relevant for how readers process text presented in these alternative formats: age may influence reading either as a proxy for experience or through broader developmental and aging-related changes in reading and orthographic processing (Perea et al., 2008). Understanding these age-related differences requires considering how reading mechanisms evolve across the lifespan. Developmentally, young readers rely more on serial, fine-grained processing of letter identities and positions, gradually transitioning to more parallel and efficient lexical access as they gain reading experience (Acha & Perea, 2008). In adulthood, however, aging leads to declines in early visual stages and orthographic processing, causing older readers to depend increasingly on lexical-level information, with a reduced impact of lower-level orthographic detail (MacKay & Abrams, 1998; Spieler & Balota, 2000; Froehlich et al., 2016). Older adults show deficits on tasks that depend heavily on high-spatial-frequency visual information (e.g., Coyne, 1981; Thapar et al., 2004), and performance in tasks such as masked letter discrimination declines substantially with age. Conversely, although lexical-decision tasks often show apparent aging effects, more integrative analyses suggest that these effects may reflect peripheral encoding or general decision processes rather than deficits in lexical-semantic processing per se. Three examples are particularly relevant. First, diffusion-model analyses indicate that older adults' slower lexical-decision responses can be attributed partly to more conservative response criteria, rather than to poorer lexical evidence accumulation (Ratcliff et al., 2004). Second, entropy-based measures that integrate response time and accuracy suggest age-related decrements in peripheral encoding, but not necessarily in central semantic processing (Allen et al., 2004). Third, slope-and-intercept analyses point to a similar conclusion: age differences in semantic-memory tasks are expressed primarily as intercept shifts, whereas episodic-memory tasks show both intercept and slope changes, consistent with stronger age-related effects on central processing in episodic than semantic tasks (Allen et al., 2002).

Morphological processing is also fully preserved in advanced age (Duñabeitia et al., 2009). Normative studies also suggest that older adults often show equal or even superior vocabulary knowledge relative to younger adults, as reflected in larger lexical repertoires (Keuleers et al., 2015; Aguasvivas et al., 2020). Moreover, individual differences in vocabulary and print exposure can mitigate some age-related deficits, enabling more efficient lexical processing despite the general effects of aging (Cohen-Shikora & Balota, 2016). Consistent with this view, older adults show greater impairments in peripheral letter encoding for visually demanding formats like mixed-case and unfamiliar fonts, particularly in terms of speed and efficiency (e.g., Allen & Madden, 1989; Allen et al., 1993; Allen et al., 2002, 2011; Mayall, 2001, 2002). While these studies indicate that aging exacerbates difficulties under nonstandard visual conditions, how specific atypical formats are processed across the adult lifespan remains underexplored, particularly for LEET and for direct contrasts between lowercase and uppercase word recognition, as prior work has typically relied on age-homogeneous samples and limited case manipulations. In addition, most studies have been done with single word lexical decision (with masked priming sometimes), that do not require any integration of meaning across words.

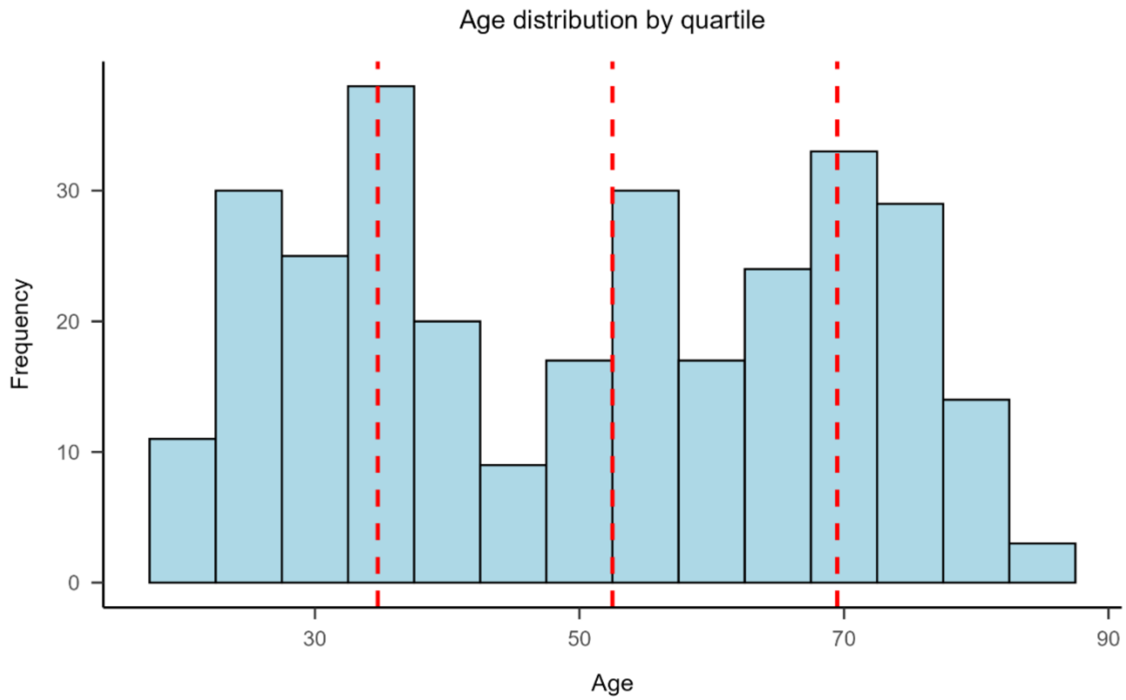
The present study fills these gaps by testing adults with ages ranging from 18 to 84 years and examining how integration of phrase meanings in conventional (lowercase, uppercase) and unconventional (mixed-case, LEET) text formats vary across the adult lifespan. Specifically, it builds on prior research that examined these formats individually to trace how case and format effects change over the course of adult life. Our study seeks to determine whether a stable preference for one case emerges or shifts with age, examining whether age-related changes in analytic/holistic processing balance and letter encoding efficiency modulate the disruptions caused by atypical orthography.

Methods

Participants

The sample consisted of 303 native English speakers (55% women, 44.7% men, 0.3% other), aged 18-84 years, recruited via Prolific Academic (Palan & Schitter, 2018). Figure 1 shows the age distribution of participants (mean = 50.81 years, SD = 18.67, range 18-84). Participants were divided into four age-based quartiles of equal size (n = 75 each). The mean ages for Q1, Q2, Q3, and Q4 were 27.1, 41.3, 60.2, and 74.6 years, respectively, with corresponding age ranges of 18–34, 35–52, 53–69, and 71–84 years. Participants provided written informed consent for their involvement in accordance with the Declaration of Helsinki. The study protocols were approved by the Research Ethics Committee at Nebrija University (UNNE-2022-0017). Participants were recruited using Prolific's age and language-screening filters. Eligibility was restricted to native English speakers, and recruitment was designed to sample broadly across the adult lifespan. We did not administer a formal neuropsychological screening instrument for mild cognitive impairment; consequently, we cannot rule out the possibility that some older participants had undiagnosed cognitive impairment. The sample should therefore be interpreted as a broadly recruited adult lifespan sample rather than as a neuropsychologically screened healthy-aging cohort.

Figure 1. Distribution of participants' ages across quartiles (quartile boundaries indicated by dotted red lines).



Materials

The stimuli consisted of 27 unique English sentences presented in four orthographic formats (lowercase, uppercase, mixed-case and LEET), for a total of 108 sentence stimuli. The 27 unique sentence stimuli resulted from creating all possible combinations of three colours (*green*, *orange* and *white*), three numbers (*five*, *eight* and *nine*) and three animals (*rabbit*, *elephant* and *tiger*), after which each sentence was rendered in the four orthographic formats. The LEET numbers employed were: A = 4, E = 3 and I = 1. Sentences followed the structure 'There are [Number] [Colour] [Animal]' (lowercase: 'There are eight orange elephants'; uppercase: 'THERE ARE EIGHT ORANGE ELEPHANTS'; mixed-case: 'ThErE aRe EiGhT oRaNgE eLePhAnTs'; LEET: 'TH3R3 4R3 31GHT 0R4NG3 3L3PH4NTS'). The presentation order was randomized for each participant. All participants read each of the 108 total sentences once. In addition to the sentences, square icons representing the three animals, three numbers and three colours were built to use in the memory check after each sentence (see Figure 2 below).

Task and Procedure

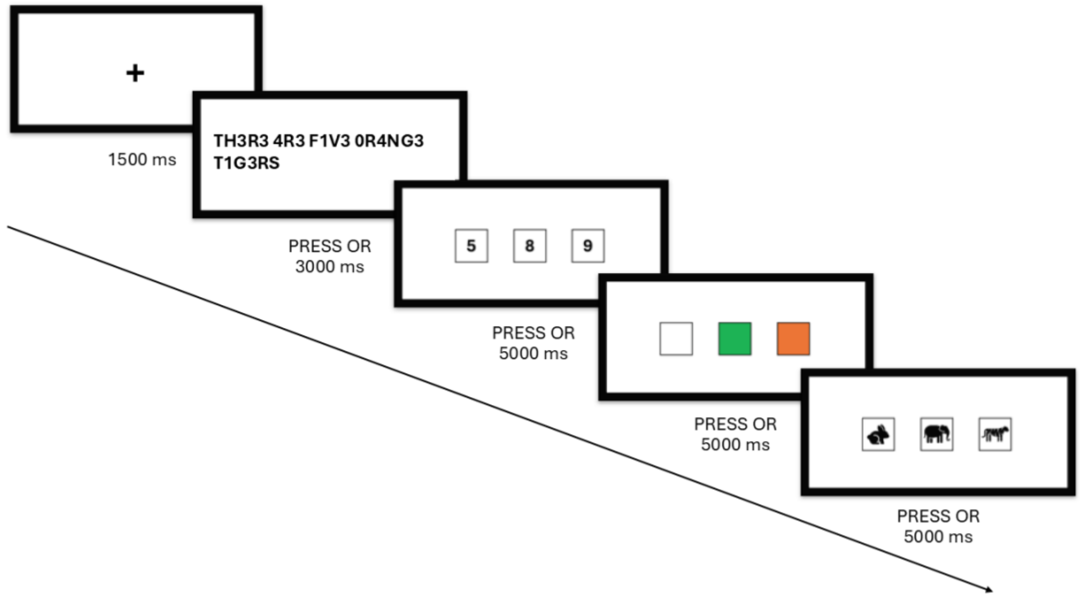
The experiment was conducted using Gorilla (Anwyl-Irvine et al., 2020), an online experiment builder and testing platform that allowed for accuracy and reading times to be automatically recorded. All sentences were displayed in Courier font, size 55. Participants completed the task within a maximum of 45 minutes, including a scheduled break halfway through the experiment.

The procedure began with an instruction screen that clearly explained the task. This was followed by a short practice phase consisting of four trials—one for each typographic format—to familiarize participants with the procedure. Upon completing the practice, a screen informed participants that the experimental task was about to begin. A progress bar was displayed throughout the experiment to indicate how much of the task remained.

Each trial followed a fixed timeline. First, a fixation cross appeared at the centre of the screen for 1500 ms to focus participants' attention and to standardize trial onset. Immediately afterward, the target sentence was presented along with the prompt "Press after reading." This prompt remained visible throughout the sentence display. Participants had a maximum of 3000 ms to read the sentence and press the spacebar. If they did not press the spacebar within this time, the sentence disappeared automatically and the experiment advanced to the next phase.

Following the reading phase, a memory check was conducted through three successive screens. In each screen, participants had to identify one of the key elements mentioned in the sentence: a number, a colour, or an animal. All the possible options for each element were displayed on each screen, and participants were required to select the one that corresponded to the sentence they had just read by clicking on the correct option. Each response screen had a maximum duration of 5000 ms; if no response was provided within this time, the trial was marked as a timeout. Two dependent variables were analysed: reading time and memory accuracy. Reading times were recorded as the latency between sentence onset and the participant's keypress. Memory accuracy was calculated as the percentage of correct selections across the three probes presented in each trial—i.e., a trial was considered correctly answered only if all three questions pertaining to that trial were answered correctly.

Figure 2. Examples of the task interface participants were exposed to. The first two screens depict the initial fixation plus reading sequence. The remaining three screens show the multiple-choice probes the participant performed to assess the meaning-integration of the phrase. *Note:* for readability, the font size in the figure has been increased, rendering two lines in the sentence screen. Sentences in the original experiment were displayed only on one line.



Results

Accuracy

While our analyses focus predominantly on reading times, measuring accuracy was a necessary check to ensure that participants were reading the sentences. Sentence memory was considered accurate only when all three questions—regarding number, colour and animal— were answered correctly. From the original sample of 303 participants, three were excluded due to low accuracy scores, < 67% (i.e., fewer than 2/3 questions correct), which indicated a lack of attention to the task.

As expected, the proportion of accurate trials in the image selection task was high: for trials with lowercase text it was 0.966 (SD = 0.055), for uppercase it was 0.960 (SD = 0.067), for mixed-case it was 0.966 (SD = 0.061), and for LEET it was 0.943 (SD = 0.084). This shows that, overall, participants were able to read and understand the simple sentences regardless of format, and that they were paying attention to the task.

Given the numerical differences across orthographic formats, we analyzed post-reading recognition accuracy using a generalized linear mixed-effects model with a binomial family, fit with glmer from the R package lme4 (Bates et al., 2015). Following the general principle of including the most complex random-effects structure justified by the design, when possible (Barr et al., 2013), we fit the maximal model that converged without singularity. The final model included fixed effects of Condition, Age, Trial, the Condition × Age interaction, and the Trial × Age interaction, with random intercepts for Participant and Item:

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glmer(Accuracy ~ Condition * Age_centered +
        Trial_centered * Age_centered + (1 | Participant) +
        (1 | ItemN), family = binomial)
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Accuracy data were analyzed at the probe-response level (n = 97,200 observations). Descriptive statistics by orthographic format are reported in Table 1. LEET served as the reference level for the Condition factor. The model revealed a significant main effect of Age, $\beta = -0.0115$, $SE = 0.0046$, $z = -2.53$, $p = .011$, indicating that post-reading recognition accuracy decreased with age. There was also a significant main effect of Trial, $\beta = 0.0043$, $SE = 0.0010$, $z = 4.51$, $p < .001$, indicating that accuracy increased over the course of the experiment.

Accuracy was also affected by orthographic format. Compared with LEET, post-reading memory accuracy was significantly higher for lowercase sentences, $\beta = 0.575$, $SE = 0.096$, $z = 6.02$, $p < .001$; uppercase sentences, $\beta = 0.391$, $SE = 0.092$, $z = 4.24$, $p < .001$; and mixed-case sentences, $\beta = 0.575$, $SE = 0.095$, $z = 6.02$, $p < .001$. Thus, LEET yielded lower post-reading recognition accuracy than the other three orthographic formats.

The Condition × Age interactions were not significant for lowercase relative to LEET, $\beta = -0.0013$, $SE = 0.0043$, $z = -0.30$, $p = .767$, or for mixed-case relative to LEET, $\beta = 0.0005$, $SE = 0.0043$, $z = 0.12$, $p = .909$. The Uppercase × Age interaction was marginal, $\beta = 0.0078$, $SE = 0.0041$, $z = 1.89$, $p = .059$, suggesting weak evidence that the age-related decline in accuracy may have been smaller for uppercase than for LEET. Importantly, the Trial × Age interaction was significant, $\beta = 0.00021$, $SE = 0.00005$, $z = 4.15$, $p < .001$. A likelihood-ratio comparison confirmed that adding the Trial × Age interaction improved model fit, $\chi^2(1) = 17.50$, $p < .001$. This indicates that trial-related improvement in accuracy was stronger among older participants, consistent with practice, task familiarization, or adaptation to the restricted stimulus set over the course of the experiment.

To summarize, these results indicate that LEET imposed the greatest cost on post-reading recognition, that accuracy declined with age, and that participants—particularly older participants—showed evidence of improved accuracy as the experiment progressed.

Figure 3. Predicted accuracy and reading time as a function of age, based on a generalized linear mixed-effects model described in the main text with a Format × Age interaction. Coloured lines represent the estimated marginal means for each format, with shaded ribbons indicating 95% confidence intervals.

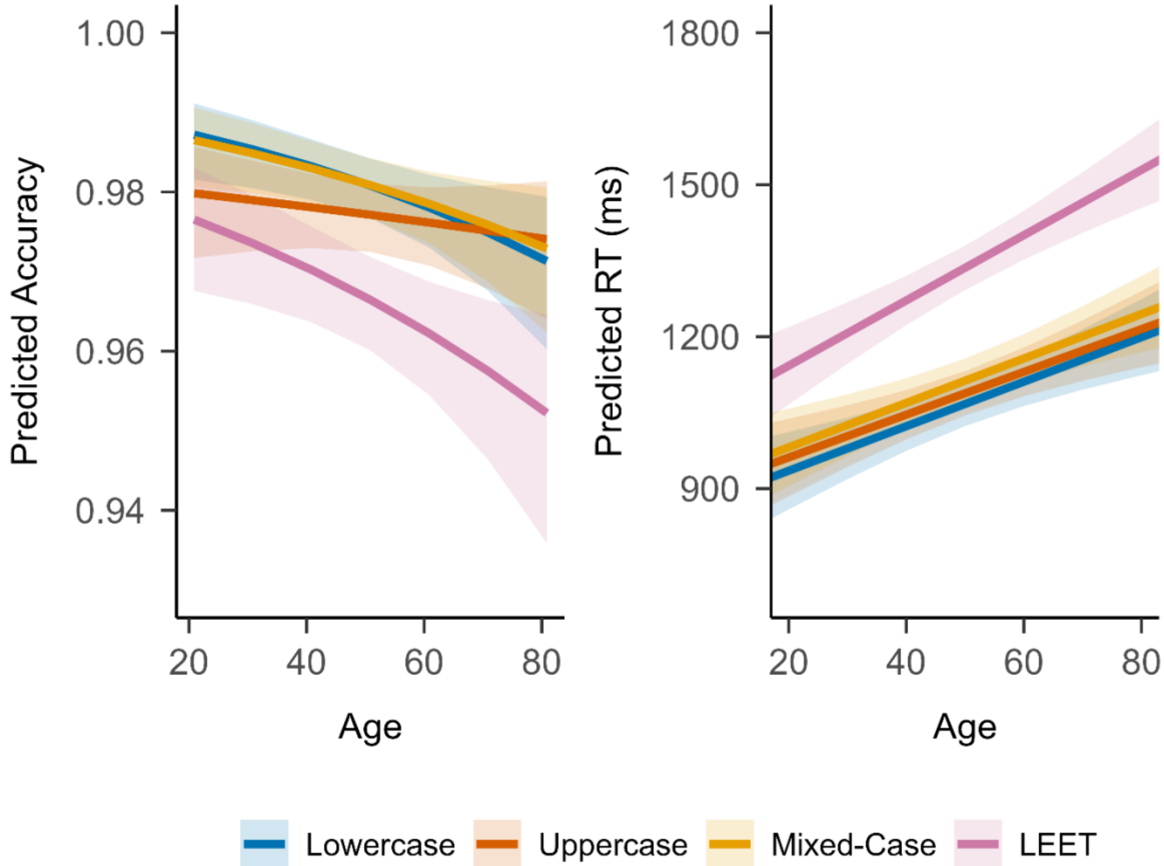


Table 1. Proportion corrects and mean Reading Times (ms) by presentation format.

Format	Correct	SD	Mean RT	SD (by participant)
Lowercase	0.966	0.055	1067	323
Uppercase	0.960	0.067	1088	328

Mixed-Case	0.966	0.061	1117	340
LEET	0.943	0.084	1322	343

Note. SD for proportion correct computed across participants; SD for reading times computed by participant.

Reading Times

Reading times associated with correct responses were analyzed. In addition, reading times shorter than 250ms (0.74% of all trials) and longer than 2500ms (2% of all trials) were eliminated.

Table 1 shows the mean and standard deviation (calculated across participants) for the four presentation formats. Reading time was fastest for lowercase and slowest for LEET, with uppercase and mixed-case clustering closer to lowercase (21 and 50 ms slower than lowercase, respectively, vs. 255 ms slower in the case of LEET). These analyses were followed by exploratory data visualizations to examine the distributional features of the observed effects via delta plots.

To analyze the effects of presentation format and participant age on reading times, we used a linear mixed-effects model using the lmer() function with the *lmerTest* package in *R* (Kuznetsova et al., 2017).

Lmer(RT ~ Age * Format + TrialOrder + (1 | Participant) + (1 | Item))

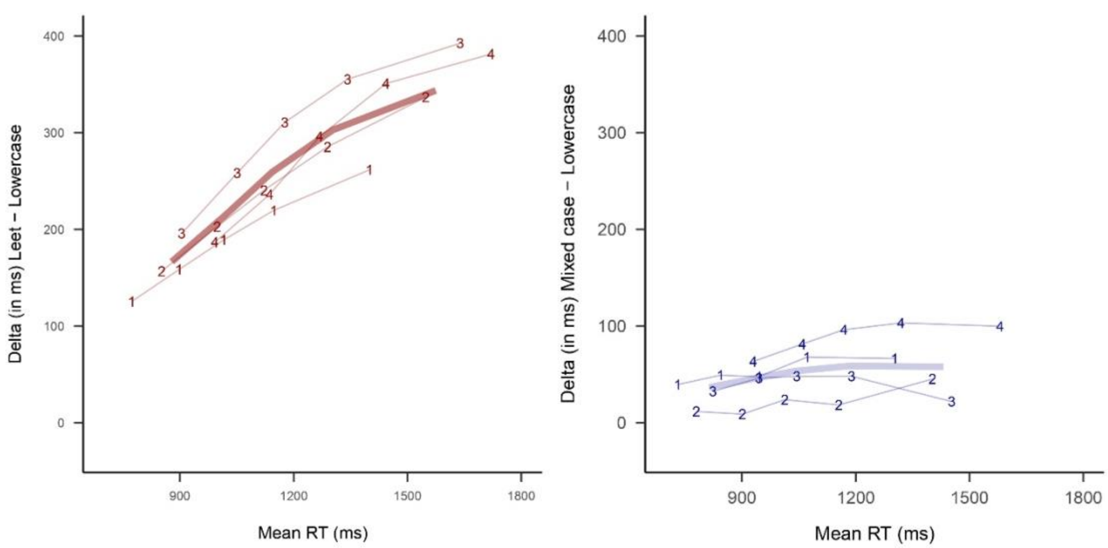
In this model, Format, Age and their interaction were specified as fixed effects, and random intercepts were included for Participant and Item. LEET served as the reference level for the Format factor. Trial Order (centered) was included in the model as a covariate to control for potential practice or fatigue effects over the course of the session. We retained a random-intercepts-only structure for subjects and items because more complex random-effects specifications led to singular fits, indicating that the data do not support estimating additional variance components reliably.

Reaction Time data (n = 26,226 observations) were analysed through a linear mixed-model analysis. Results showed a significant main effect of Age (centred), $F(1, 262.7) = 22.48$, $p < .001$, demonstrating that reaction times increased as a function of age. Furthermore, a significant main effect of Format was found, $F(3, 102.9) = 118.95$, $p < .001$. Reading times in sentences displayed in LEET format were significantly slower than in any other format (LEET vs. lowercase: β = -273.3, SE = 16.38, t(103.2) = -16.68, $p < 0.001$; LEET vs. uppercase: β = -250.6, SE = 16.38, t(103.3) = -15.30, $p < 0.001$; LEET vs. mixed-case: β = -225.72, SE = 16.38, t(103.3) = -13.77, $p < 0.001$). A significant main effect of Trial Order was also observed, F(1, 25,867.7) = 1627.16, $p < .001$, showing that participants identified the words faster over the course of the experiment. Notably, a significant Age × Format interaction was found, F(3, 25,840.7) = 28.77, $p < .001$, indicating that age-related slowing was more pronounced for the LEET format than for the other formats. In other words, while reading times increased with age across all formats, age-related slowing was particularly pronounced for the LEET format compared to the others. Figure 3 illustrates this pattern, showing a clear separation between LEET and the remaining formats, as well as a general increase in reading times with age.

To examine condition-specific Age slopes, the model was reparametrized by changing the reference level of the Format factor (using treatment coding), so that each orthographic format's Age slope appeared directly as a fixed effect in the model output. Follow-up analyses showed that the slopes relating Age to reading time were significantly less steep for lowercase (β = –2.11, SE = 0.28, t(25840) = –7.46, $p < 0.001$), uppercase (β = –2.27, SE = 0.28, t(25840) = –7.99, $p < 0.001$), and mixed-case (β = –2.12, SE = 0.28, t(25840) = –7.47, $p < 0.001$). To directly estimate the age slope for LEET, the model was reparametrized with Lowercase as the reference level, revealing a significant increase in reading time with age for LEET sentences (β = 2.11, SE = 0.28, t(25,840) = 7.46, $p < .001$).

Exploratory Data Analysis. To complement the mixed-effects analyses of mean reading times, we conducted an exploratory data analysis (EDA) of the response-time distribution. EDA refers to descriptive and visualization-based analyses used to inspect patterns in the data beyond the primary confirmatory modeling. In the present case, this approach allowed us to examine whether orthographic-format costs were constant across the response-time distribution or became larger among slower responses. This distinction is theoretically important because these two possible patterns (flat delta plot: constant cost, vs sloped delta plots: larger effects for slower responses) indicate qualitatively different effects. We therefore constructed Vincentile-based delta plots using the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles of correct-response reading times. To construct these plots, we first computed each participant's reading-time quantiles separately for each orthographic condition. We then averaged the corresponding quantiles across participants to obtain group-level Vincentiles for each condition. For each pairwise comparison, the x-axis value at each quantile was computed as the mean of the two condition-specific Vincentiles being compared, whereas the y-axis value was computed as their difference. Thus, each point represents the orthographic-format cost at a given location in the reading-time distribution. Lowercase sentences served as the baseline format, and deltas were computed for mixed-case, and LEET formats relative to this baseline (the delta plot for the lowercase-uppercase comparison is not shown for the sake of simplicity, but it is available in the OSF repository for the study).

Figure 4. Vincentile-based delta plots comparing reading times for LEET and mixed-case sentences relative to lowercase sentences. Delta values were computed at the 0.1, 0.3, 0.5, 0.7, and 0.9 quantiles of correct-response reading times. The x-axis represents the mean RT for the two conditions being compared at each quantile, and the y-axis represents the RT difference between conditions. Thick lines show the overall delta functions, and thinner lines show delta functions computed separately for age-based quartiles, labeled 1 through 4 from youngest to oldest. The LEET–lowercase contrast showed large positive deltas that increased at slower Vincentiles, particularly among older participants. In contrast, the mixed-case–lowercase contrast showed smaller and flatter deltas, indicating a more uniform cost across the RT distribution.



To examine whether these distributional patterns varied across ages for the mixed-case and LEET conditions, we divided participants into age-based quartiles and constructed delta plots separately for each quartile. Figure 4 shows the overall delta functions as thick lines, with quartile-specific delta functions overlaid and labeled 1 through 4, corresponding to increasing age. The LEET–lowercase contrast showed a strongly positive and upward-sloping delta function. This pattern was especially pronounced for the 3rd and 4th quartile ages, but is qualitatively similar to the 1st and 2nd quartiles. On the other hand, the flat delta plot for the mixed case is higher for the oldest participants, but it does not appear to have a slope similar to that for the LEET-lowercase comparison.

Discussion

The goal of this study was to examine how variations in typographical formats (lowercase, uppercase, mixed-case, LEET) affect reading times and memory for the read sentences across the adult lifespan (18-84 years), building on established effects like lowercase superiority (Perea et al., 2017, 2020) and case-mixing costs (Mayall et al., 1997). As noted in the introduction, it was expected that LEET would involve longer reading times, suggesting a higher cognitive load compared to conventional formats (lowercase, uppercase, mixed-case).

The results confirmed these predictions. Conventional formats yielded the fastest reading times and high accuracy, mixed-case imposed moderate costs, and LEET generated substantial disruptions in reading, accompanied by slightly reduced recognition. Although accuracy remained high across all formats, reading sentences in the LEET format resulted in reliably lower accuracy across age groups.

Crucially, analyses of reading times revealed that the disruptive effect of LEET increased with age, whereas age-related slowing was less pronounced for conventional formats, yielding a significant Format by Age interaction that would not be observable in age-homogeneous samples. These results are consistent with prior research documenting the lowercase superiority effect, whereby lowercase words are processed faster and more efficiently than uppercase ones (Perea et al., 2017; Vergara-Martínez et al., 2020; Perea et al., 2020). They also align with evidence that orthographic distortions, such as case mixing, disrupt reading fluency by breaking familiar visual regularities and increasing processing demands (Arditi & Cho, 2007; Mayall et al., 1997; Tinker, 1963).

Beyond mean effects, delta-plot analyses delineate the nature of these processing costs. Vincentile-based delta plots comparing Lowercase with LEET and mixed-case formats showed qualitatively different effects for LEET vs mixed-case. Notably, the lowercase-LEET contrast exhibited steeper slopes toward slower responses—particularly in older participants—suggesting that LEET engages processing mechanisms that place disproportionate demands on perceptual encoding and integration as reading unfolds. This pattern extends masked priming findings, in which visually similar LEET primes can activate lexical representations (Carreiras et al., 2007; Kinoshita et al., 2014), to naturalistic reading contexts where age-related constraints amplify the costs of orthographic distortion.

One of our goals was to explore whether age-related advantages due to increased exposure to reading with age might modulate the disruptions triggered by the atypical orthography in our experiment. We arrive to a split-decision on this issue: The difference between LEET and mixed-case illuminate how distortions differentially tax visual word recognition mechanisms: while mixed-case preserves abstract letter identity access through standard alphabetic characters (Fournet et al., 2022), LEET imposes additional symbol-to-letter recoding demands, as evidenced by delta plots showing costs magnified for slower responses (Perea et al., 2008).

Age modulated these format effects in a manner consistent with prior evidence of heightened vulnerabilities in older adults' under visually demanding conditions, particularly at early perceptual and pre-lexical stages of processing (Allen et al., 2002, 2004; Mayall, 2001, 2002) rather than reflecting age-related changes in lexical representations per se (Perea et al., 2008). Specifically, disruption in the LEET format amplified with age while the disruption caused by mixed-case format showed comparatively smaller age-related costs and a flat delta plot pattern.

This Format × Age interaction indicates that aging exacerbates the impact of orthographic irregularities that degrade visual regularities feeding into the lexical system, without implying a general decline in lexical processing. In this sense, LEET appears to place disproportionate demands on perceptual encoding and integration mechanisms that precede lexical access, thereby revealing age-related differences that are not apparent for visually canonical formats in age-homogeneous samples.

Taken together, these results suggest that the mechanisms underlying LEET processing differ qualitatively from those involved in case mixing. Whereas mixed-case disrupts global visual regularity, LEET requires an additional layer of symbol-to-letter recoding that particularly taxes older readers, whose analytic processing resources are more limited (Allen et al., 2011). Age effects were most pronounced for LEET: while younger readers tolerated LEET through flexible letter identity normalization (likely reflecting both digital exposure and preserved early visual processing), older adults showed disproportionate slowdowns and accuracy losses in the memory probes. This interpretation is further supported by delta plot analyses, which revealed that the cost of LEET increased disproportionately for slower responses, and aligns with lifespan shifts toward holistic, vocabulary-supported routes where compensatory lexical gains (Keuleers et al., 2015; Aguasvivas et al., 2020) preserve comprehension but cannot offset early perceptual demands (Spieler & Balota, 2000; Cohen-Shikora & Balota, 2016). Consequently, while the lowercase advantage and mixed-case disruption have been established before, our findings extend the literature by demonstrating how LEET's unique processing demands interact with age-related declines in peripheral orthographic encoding.

From a practical perspective, these findings underscore the challenges that unconventional formats such as LEET impose on reading efficiency and comprehension, particularly for older adults. Unlike children's gradual abstraction of case-invariant letter identities across conventional formats (Grainger, 2022), adult aging reveals limits to this abstraction under extreme orthographic distortion: while developmental gains reflect experience-driven parallelization of skilled reading (Acha & Perea, 2008; Perea et al., 2017), aging reverses this efficiency for visually irregular formats like LEET. Although our data did not directly measure participants' prior exposure to LEET, the consistently slower reading times and reduced accuracy (disproportionate in older adults) suggest that familiarity alone may not be sufficient to compensate for LEET's demands on residual analytic resources beyond what compensatory lexical mechanisms can offset (Vergara-Martínez et al., 2020).

Naturally, this study contains some limitations. First, the experimental materials consisted of short, artificial sentences and limited LEET substitutions (A=4, E=3, I=1), constraining ecological validity since real LEET use involves diverse, context-specific substitutions encountered in chat messages and gaming environments. Second, participants' prior familiarity with LEET was not measured, even though previous exposure, and age as its proxy, could plausibly modulate both accuracy and reading times, limiting causal attribution between format per se and processing costs. Third, the restricted stimulus set involved repeated exposure to the same sentence constituents across trials, although no sentence was repeated within a given orthographic format. This repetition was useful for maintaining close comparability across conditions and for estimating distributional properties of reading times, but it may also have promoted learning or adaptation over the course of the experiment. In particular, participants may have become increasingly efficient at mapping recurring numbers, colors, and animals in unconventional formats such as mixed case or LEET onto their corresponding words.

Future work should therefore incorporate more ecological tasks, such as real chat messages or online conversations, to better approximate the contexts in which LEET is typically encountered. Moreover, combining behavioral measures with eye-tracking and EEG would provide a more precise characterization of the perceptual and lexical integration processes involved. In addition, a forthcoming study with Spanish participants residing in Morocco will explore these aspects in individuals regularly exposed to Darija, a dialect of Moroccan Arabic whose writing system incorporates the LEET format. Such a population offers a valuable opportunity to determine whether sustained exposure to LEET reduces its processing costs, thereby clarifying the extent to which familiarity and linguistic environment can mitigate the cognitive challenges posed by unconventional orthographic formats across development, adulthood, and aging.

In conclusion, this study demonstrates graded orthographic processing costs (conventional formats < mixed-case < LEET) that interact with age across the adult lifespan (18-84 years), confirming established effects like lowercase superiority and case-mixing disruption while revealing LEET's unique symbol-to-letter recoding demands. By tracing format effects from young adulthood to advanced age, these findings integrate developmental, adult, and aging research, highlighting analytic processing decline as the critical vulnerability to digital orthographies. The current study not only contributes to the basic science of reading, but results advance equitable typography guidelines for education, digital design, and communication contexts that minimize age-related barriers across digital ecosystems.

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Competing interests

The authors declare no competing interests.