Aging Changes the Word-Length Effects in Chinese Reading: Insights from co-registering EEG data to eye movements

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Abstract

Background: Previous research has observed larger word length effects in Chinese reading, speculating that older adults may adopt a character-based processing strategy for recognizing long words. However, to our knowledge, there was no direct evidence to support this viewpoint. Methods: By co-registering EEG data to eye tracking, we investigated how aging affects word length effects in natural Chinese reading. Results: Our results revealed larger word-length effects on fixation time measures among older adults than in younger adults. Concerning EEG data, we observed inverse word-length effects on the earliest components and later N400, with word length decreasing amplitudes for older adults. No age-related differences in the word-length effect were observed in the P600 component. Conclusions: Overall, our findings suggest that older adults adopt a character-based processing strategy for recognizing long four-character words, and a similar mechanism to younger adults for integrating words during reading comprehension.

Full Text

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Conclusions: Overall, our findings suggest that older adults adopt a character-based processing strategy for recognizing long four-character words, and a similar mechanism to younger adults for integrating words during reading comprehension.

Keywords: older adults reading; word-length effects; Chinese reading; fixation-related potentials

Introduction

Word length is an essential parameter that influences how easily words can be decoded in reading. Short words receive fewer fixations, shorter reading times, and are skipped less frequently than long words (Gollan et al, 2011; Kliegl et al, 2004; Rayner et al, 2011). Evidence supports that word length effects in alphabetical script reading are preserved among older adults. For example, Malsburg et al. (2015) revealed no reliable age change in word-length effects on scan-path (von der Malsburg et al, 2015). It was also confirmed that the distributions of fixation landing positions on long words were comparable across younger and older adult readers (Pollatsek et al, 2006), and that fixation location effects on both short- and long-English word identification were well preserved from aging (Li et al, 2017). Empirical evidence indicates that the removal of interword spaces disproportionately impairs reading performance in older adults compared to younger adults, thus highlighting the essential role of word spacing in preserving word length and fixation landing position effects during aging (McGowan et al, 2014, 2015; Rayner et al, 2013).

It is valuable to examine how preserved word length effects among older adult readers in alphabetical script reading generalize to non-alphabetical scripts such as Chinese, which has many unique characteristics. In Chinese writing systems, the basic orthographic unit consists of square-shaped characters, and word boundaries are not demarcated by spaces. Most words are composed of multiple characters, with each character having its own semantic meaning that may contribute to the whole word meaning. Despite rigorous evidence supporting the importance of word recognition for text comprehension (Bai et al, 2008), characters are also processing units and play a role in eye movement (Chen et al., 2003; X. Li et al, 2014; Yan et al, 2006). Li and Pollatsek (2020) and colleagues proposed a model proclaiming that word decoding involves processing of the whole word, its constituent characters, and their interactions (X. Li & Pollatsek, 2020). Probing Chinese word length effects and their aging is beneficial for understanding the word and character processing mechanisms underpinning reading.

One important justification for investigating aging impacts on word processing in Chinese reading is that, as we know, older Chinese readers use different oculomotor strategies compared to alphabetical older adults. Specifically, older adults exhibit increased fixation frequency and duration, more regressions, longer progressive saccades, and greater word-skipping behavior compared to younger adults during English text reading (McGowan et al, 2014; Pollatsek et al, 2006; Rayner et al, 2009), suggesting they may adopt a risky strategy to complement the decline in cognitive processing (Pollatsek et al, 2006; Rayner et al, 2011). In contrast, Chinese older adults made more and longer fixations but were less likely to skip words, suggesting they employ a more careful strategy (Liu et al, 2017; Wang et al, 2018). Research on this topic contributes to understanding both universal processing mechanisms underpinning reading and unique processing mechanisms of the Chinese language.

Contrary to patterns observed in alphabetic scripts (e.g., English), Chinese older adults failed to demonstrate preserved word-length effects. Specifically, Li et al. (2018) observed that older adults had larger word-length effects on fixation measures than young adults, while they landed their saccades more rarely at optimal intraword locations and generated more refixations on long words during reading (S. Li et al, 2018). In addition, fixation landing position distribution and its impact on word recognition were not preserved for Chinese older adults. Specifically, Liu et al. (2015) found that the optimal viewing position effect in Chinese word identification was absent among older adults, who demonstrated peak recognition efficiency when initial fixations were positioned on the first character across all word lengths (two-, three-, and four-character words; P. Liu et al., 2015). They argued that older adults may adopt character-based strategies to comprehend Chinese texts (S. Li et al, 2018; P. Liu et al, 2015).

In the present study, we aimed to establish whether older Chinese adults use a different character-based mechanism compared to their younger counterparts for producing word length effects. There are compelling reasons to suppose they use character-based mechanisms. First, parafoveal vision decline, smaller perceptual span, and reduced parafoveal processing were observed for older adults (He et al, 2021; Owsley, 2011; Zhang et al., 2019), which might impact target saccades and lead them to make more effort to decode long words. Second, the lack of optimal viewing position effects for older adults suggested they adopt a character-based strategy to decode words (S. Li et al, 2018; P. Liu et al, 2015). Nevertheless, there is evidence supporting that older adults may use similar word-based mechanisms for producing larger word length effects. For instance, an eye tracking study revealed that older and young adults share similar effects of contextual plausibility on word segmentation (L. Li et al, 2024).

Eye tracking measures merely reflect the final outcomes of information processing and are thus insufficient for elucidating the cognitive mechanisms underlying the enhanced word length effects observed in older adults. Larger word-length effects for them can be interpreted as they use character-based strategies for reading (S. Li et al, 2018; P. Liu, 2015) or they simply need more effort to decode long words. Event-related potentials (ERP) provide continuous measures of neurocognitive processing and are quite suitable for addressing this issue. Thus far, however, most ERP studies have focused on how young adults unfold word-length effects in alphabetical script reading. In an ERP study, for instance, sentences were displayed with rapid serial visual presentation paradigm (RSVP), which demonstrated augmented word-length effects manifested as early negativity (peaking around 200 ms) distributed across occipital and parietal electrode sites (Van Petten & Kutas, 1990). A subsequent lexical decision study revealed word-length effects occurred substantially early and faded at later intervals (Barr et al., 2013; Bates et al., 2015, 2015; Cai & Brysbaert, 2010; Dimigen, 2020; Hauk et al., 2006, 2009; Hauk & Pulvermüller, 2004; Hutzler et al., 2007; X. Li et al., 2011; Nasreddine et al., 2005; Sereno et al., 2020). Despite the growing body of research on Chinese reading, the neural dynamics underlying age-related differences in word length effects have yet to be examined using event-related potential methodology.

Several shortcomings of ERP studies should be highlighted. First, whether findings derived from isolated lexical decision paradigms adequately capture the complexity of contextual reading processes warrants further investigation. Second, the RSVP paradigm used in reading research interrupts natural attention deployment, parafoveal preview, and precludes word-skipping (Hutzler et al, 2007, 2013), thus diminishing their ecological validity. To overcome these shortcomings, we simultaneously recorded EEG and eye movement data to examine age-related differences in word length effects in free-view Chinese reading. With this co-registration technique, the EEG data are time-locked to the first fixation onsets on target words, thus generating fixation-related potentials (FRPs). The FRP waveforms resemble those of ERP, which shed light on neural correlates of word processing in natural reading. To date, the application of co-registration methodology to investigate this phenomenon in ecologically valid Chinese reading contexts has not been reported.

This study employed EEG-eye movement co-registration to examine how aging modulates word length effects in Chinese text processing. The primary objective was to delineate the cognitive mechanisms responsible for the age-related increase in word length effects on fixation time measures. Specifically, this investigation examines whether aging influences the transition from word-based to character-based processing strategies among Chinese readers during the decoding of long words. We hoped to replicate larger word length effects for older adults than their younger counterparts on fixation time measures. We mainly focused on the FRP data. This study represents an account of whether older adults adopt a character-based strategy for decoding long words, predicting reversed word length effects for older adults compared with young adults; otherwise, larger word length effects should be observed for older adults compared with young adults.

Methods

Participants

To ensure comparability with previous findings in eye-tracking studies for Chinese-sentence reading and word decision-making (S. Li et al, 2018; P. Liu et al, 2015), we used a similar sample size. The excluded data, as well as the measures of eye movements and fixation-related potentials and manipulations, are reported below. The data were collected between 2021 and 2022. A total of 46 participants were recruited from the local community, comprising 20 older adults (13 females, 7 males) and 26 younger adults (19 females, 7 males). All participants reported normal reading abilities and no history of cognitive, mental, or physical disorders. Older adults ranged in age from 60 to 73 years ($M = 61.80$, $SD = 2.84$), while younger adults ranged from 19 to 25 years ($M = 20.04$, $SD = 1.51$).

Using a Tumbling E chart, both groups were screened for normal visual acuity, with no reliable group difference (old group: $M = 4.99$, $SD = 0.09$; young group: $M = 4.97$, $SD = 0.11$; $t = 0.704$, $p > 0.05$). No significant difference in years of education was observed between older adults ($M = 11.25$, $SD = 2.36$) and younger adults ($M = 12.12$, $SD = 1.97$; $t = 1.357$, $p > 0.05$). Participants were required to be native speakers of Chinese and received ¥150 as compensation (approximately 21 USD). The Montreal Cognitive Assessment (MoCA) was administered to ensure normal cognitive functioning in older adults, with a minimum score of 26/30 required for inclusion (Nasreddine et al, 2005).

The Chinese-adapted Vocabulary subtest of the Wechsler Adult Intelligence Scale-Third Edition (WAIS-III) (Wechsler et al., 2003) was administered to assess vocabulary knowledge. Independent samples t-test revealed no significant difference between older adults ($M = 14.85$, $SD = 0.93$) and younger adults ($M = 14.38$, $SD = 1.13$; $t = 1.487$, $p > 0.05$). However, younger adults demonstrated significantly higher digit span scores ($M = 14.35$, $SD = 1.52$) than older adults (M = 11.55, SD = 1.73; $t = 5.819$, $p < 0.001$).

Design and Materials

The experiment followed a 2 (length of target word: short vs. long) × 2 (group: younger vs. older adults) design. One hundred and sixty-four framed sentences containing target words were used. Examples are presented in Figure 1 [Figure 1: see original paper]. The complete set of materials is available at the Open Science Framework repository: https://osf.io/wxnk8/. Sentence stimuli varied in length from 12 to 22 characters (M = 17.45, SD = 1.93), and target words were systematically positioned at or near the midpoint of each sentence. Short condition target words comprised two characters, whereas long condition target words comprised four characters. Table 1 illustrates that short and long target words were systematically matched for character stroke frequency (wherein the third and fourth character positions in the short target word condition contained non-target characters; $|ts| < 0.93$, $ps > 0.35$). Moreover, word and character frequencies, calculated per million characters based on the SUBTLEX-CH corpus, demonstrated no significant differences between conditions ($|ts| < 1.02$, $ps > 0.31$).

Twenty undergraduate participants rated sentence plausibility on a 5-point Likert scale, revealing no significant difference between long and short word conditions (4.65 vs. 4.61, $t = 1.227$, $p > 0.05$). A cloze task involving 20 participants (10 younger and 10 older adults) assessed target word predictability. None participated in the main experiment. Mean cloze probability for short words was 0.37% (young adults) and 0.24% (older adults). For long words, cloze frequencies were 0.43% (young adults) and 0.30% (older adults). A two-way ANOVA with word length (short vs. long) as a within-subjects factor and age group (younger vs. older adults) as a between-subjects factor revealed no reliable main effects of age group, target word length, or their interaction ($Fs < 0.17$, $ps > 0.47$).

A Latin square design counterbalanced sentence frames, yielding two equivalent stimulus sets. Each set contained 164 sentence frames with equal distribution of short and long target words. Participants were randomly assigned to stimulus sets within each age group. Experimental sentences were administered in random order, with 12 practice sentences presented prior to experimental trials. Comprehension was assessed using true/false questions administered after 5 sentences during practice and after 40 sentences during experimental trials. Age-appropriate response methods were employed: younger adults used keyboard input (right or left button presses) and older adults provided verbal responses.

Apparatus and Procedure

EEG signals were recorded using 32 electrodes connected to a BrainAmp amplifier (Brain Products, Germany) at a sampling rate of 1000 Hz. The AFz electrode served as the ground reference. Horizontal and vertical electrooculogram

(EOG) channels were concurrently recorded to facilitate subsequent correction of ocular artifacts. Electrode impedances were maintained below 5 kΩ. Neural signals were digitized using an online band-pass filter of 0.1-100 Hz. Eye movement data were sampled at 1000 Hz using an EyeLink eye tracker system. Temporal synchronization between eye movement and EEG recordings was accomplished via transistor-transistor logic (TTL) pulses transmitted from the stimulus presentation computer at trial onset and offset. Fixation-related potentials (FRPs) were derived by time-locking EEG epochs to the onset of first fixations on target words. Identical fixation regions of interest were employed across both short and long target word conditions.

Testing was conducted individually. Following arrival, participants provided written informed consent and completed a visual acuity examination to ensure normal or corrected-to-normal vision. The protocol commenced with a practice phase of ten trials to acclimate participants to procedural requirements. All stimuli were rendered using 20-point Song typeface against a white background. Participants maintained a fixed viewing distance of 60 cm, ensuring each character subtended approximately 1° of visual angle. Visual stimuli were displayed on a 19-inch LCD monitor (1024$×$768 pixels, 60 Hz vertical refresh rate). Participants received instructions emphasizing reading for comprehension, followed by completion of a 3-point horizontal eye-tracking calibration procedure. Calibration accuracy was monitored before each trial, with re-calibration implemented whenever accuracy exceeded 0.5° of visual angle.

Data Analysis

Statistical analysis revealed that older adults exhibited significantly poorer comprehension accuracy than younger adults (M = 84.0% vs. M = 96.5%; $t = 5.215$, $p < 0.001$). The analysis framework comprised two sets of dependent variables: first-pass processing measures (first fixation duration, gaze duration, target word-skipping probability, and refixation probability) and reprocessing measures (total reading time, regression path duration, probability of regressions-out, and probability of regressions-in). Referencing previous eye tracking studies (S. Li et al, 2018), data preprocessing involved exclusion of fixations with extremely short and long durations. Specifically, first fixation durations and gaze durations below 80 ms or exceeding 1200 ms were excluded, affecting fewer than 3.9% of trials. These measures were analyzed using linear mixed-effects models fitted with the lme4 package (version 1.1-30, Bates et al., 2015) in R (version 4.2.1).

Linear mixed-effects models with maximal random structure were fitted to analyze eye-tracking dependent variables, incorporating full random-effects structures for both participants and items (Barr et al., 2013). When maximal models failed to converge, simplification was performed through systematic removal of random effects components, prioritizing item-level random effects before participant-level effects, with correlations among random effects removed first, followed by random slopes as needed. Word length, group, and their interactions were entered as fixed effects. Regression coefficients (b), standard errors (SE), t-statistics (t = b/SE), and p-values were reported. To ensure robustness, parallel analyses were conducted using log-transformed continuous variables, which demonstrated identical patterns of statistical significance. Given this consistency, only results from non-transformed data are presented.

EEG data were analyzed using the MATLAB toolbox EEGLAB (version 8.10). Raw EEG signals underwent offline preprocessing with a 0.1–40 Hz band-pass filter. To enhance detection of saccade-related artifacts, spike potentials were overweighted through replication of data within a temporal window extending from -20 to +10 ms around saccade events. A linked mastoid reference scheme (TP9/TP10) was applied. Ocular artifact correction was implemented using independent component analysis (ICA) methodology specifically adapted for fixation-related potential (FRP) analyses (Dimigen, 2020). Independent components were rejected if their variance during saccadic epochs exceeded corresponding fixation-epoch variance by more than 10%. Automated artifact rejection algorithms excluded trials exhibiting excessive amplitude deviations ($±$100 V) indicative of residual ocular contamination.

Event-related potentials time-locked to fixation onset (FRPs) were computed separately for each experimental condition and participant across epochs spanning -200 to +1000 ms relative to fixation onset. Mean amplitudes were quantified within theoretically motivated time windows: 100–300 ms for early components, 300–500 ms corresponding to the N400 response, and 500–800 ms encompassing the P600 component. Statistical evaluation employed omnibus repeated-measures analyses of variance (ANOVAs) according to the framework established by Sereno et al. (2020). The design incorporated two within-subjects factors: Condition (2 levels) and Region of Interest (ROI). Electrode sites were systematically grouped into nine anatomically-defined ROIs corresponding to a topographical matrix (anterior-central-posterior × left-midline-right), as depicted in Figure 2 [Figure 2: see original paper].

Results

Eye Movement Measures

Sentence-Level Analyses. Older adults spent more time comprehending sentences (4623 ms vs. 2966 ms), made more and longer fixations (fixation number: 15.9 vs. 11.4; mean fixation duration: 242 ms vs. 221 ms) and more leftward saccades (3.85 vs. 3.65), and made shorter forward saccades than younger counterparts (2.21° vs. 2.95°). These age-related differences provide further support for previous research findings (S. Li et al., 2018; Z. Liu et al., 2017; Wang et al., 2018).

Word-Level Analyses. Descriptive statistics and statistical test results are reported in Tables 2 and 3. Robust word-length effects were consistently observed across multiple dependent measures, with longer words (four characters) eliciting significantly extended gaze durations, regression path durations, and total reading times relative to shorter words (two characters). Furthermore, four-character words demonstrated elevated refixation probabilities and diminished skipping rates compared to two-character words, consistent with established word-length effects (S. Li et al., 2018; X. Li et al., 2011). Notably, first fixation duration exhibited a reversed word-length effect, with two-character words receiving longer initial fixations than four-character words, corroborating previous findings by Li et al. (2018). This phenomenon may reflect a cognitive processing strategy whereby both young and older adults exhibit reduced reliance on single prolonged fixations when decoding longer words, as substantiated by significant word-length effects on refixation probability.

Older adults exhibited systematically longer fixation durations across temporal eye-movement indices (first fixation duration, gaze duration, regression path duration, and total reading time) and demonstrated elevated refixation probabilities for target words relative to younger participants. Statistical analyses detected significant Group × Word Length interaction effects across eye-movement parameters. The interaction pattern was characterized by age-related differential responses to word-length manipulations: older adults exhibited amplified word-length effects on temporal measures (gaze duration, regression path duration, and total reading time) while showing attenuated effects on word-skipping probability compared to younger participants. Contrary to expectations based on prior research, the present study did not replicate the enhanced word-length effect on refixation probability previously documented in older adults (S. Li et al., 2018).

FRP Results

See Table 4 for statistical reporting and Figure 3 [Figure 3: see original paper] for mean amplitudes of word length differences in FRP amplitude for young and older adults.

ERP data at 100–300 ms: The ANOVA demonstrated a significant main effect of ROI, reflecting a clear anterior-posterior voltage distribution with peak negative amplitudes over midline posterior scalp regions (-3.891 V) and peak positive amplitudes over midline anterior scalp regions (2.771 V). Analysis of the word length × ROIs interaction elucidated marginally reliable increased word-length effects on negativity amplitude over midline posterior (-3.685 vs. -4.514 V, $p = 0.09$), but numerically decreased word-length effects over left anterior (1.843 vs. 1.856 V), left central (2.803 vs. 2.845 V), midline central (1.107 vs. 1.178 V), and left posterior (2.585 vs. 2.654 V). Post-hoc decomposition of the significant Group × ROI interaction revealed that younger adults demonstrated significantly more pronounced negative voltage responses over midline posterior scalp locations than older adults (-5.490 vs. -2.291 V, $p < 0.005$), but statistically reliable decreased negativity over left anterior (2.429 vs. 1.095 V, $p < 0.05$), right anterior (2.354 vs. 1.135 V, $p = 0.06$), midline central (1.742 vs. 0.363 V, $p < 0.05$), left posterior (3.155 vs. 1.924 V, $p < 0.05$), and right posterior (2.715 vs. 1.314 V, $p < 0.05$). Statistically reliable three-way interactions among group, word length, and ROIs were observed. Further tests revealed increased word-length effects on negative deflections over midline posterior for younger adults (-4.561 vs. -6.420 V, $p < 0.05$), but decreased word-length effects over nine scalp regions among the older group ($ps < 0.05$).

ERP data at 300–500 ms: Statistical analysis yielded a significant main effect of ROI, demonstrating differential topographical voltage distributions: maximal negative deflections were recorded over midline posterior electrode locations (-4.472 V), while maximal positive deflections were observed over midline anterior electrode locations (3.875 V). Testing of word length × ROIs interaction elucidated a reliable increased word-length effect on negativity amplitude over midline posterior (-4.026 vs. -5.466 V, $p < 0.05$), but no reliable effects among other scalp regions ($ps > 0.05$). Testing of group × ROIs interaction elucidated increased negativity over midline posterior for younger adults compared to older adults (-6.573 vs. -2.372 V, $p < 0.005$), but statistically reliable or numerically decreased negativity over left anterior (3.312 vs. 1.601 V, $p < 0.05$), midline anterior (4.105 vs. 2.858 V), right anterior (3.057 vs. 1.440 V, $p < 0.05$), midline central (1.877 vs. 0.216 V, $p < 0.05$), right central (2.807 vs. 1.631 V), left posterior (3.959 vs. 2.605 V, $p = 0.057$), and right posterior (3.456 vs. 1.910 V, $p < 0.05$). Further tests clarified these three-way interactions, revealing that younger adults showed increased word-length effects on negative deflection over midline posterior scalp (-5.252 vs. -7.893 V, $p < 0.05$), while older adults demonstrated decreased word-length effects over midline anterior (2.625 vs. 3.091 V, $p = 0.051$), right central (1.405 vs. 1.857 V, $p = 0.053$), left posterior (2.269 vs. 2.941 V, $p = 0.043$), and right posterior (1.602 vs. 2.218 V, $p = 0.068$).

ERP data at 500–800 ms: We revealed a reliable main length effect, with long words eliciting larger P600 than short ones (-0.571 vs. 4.005 V). A reliable main ROIs effect was observed, with the smallest positive P600 over midline posterior (-0.048 V) and the largest P600 over left anterior (3.212 V). Testing of word length × ROIs interaction elucidated a marginally reliable increased word-length effect on P600 amplitude over midline posterior (-0.287 vs. 1.943 V, $p = 0.089$), but reliable effects among other scalp regions ($ps < 0.001$). Follow-up contrasts examining the Group × ROI interaction revealed distinct age-related P600 distribution patterns. Younger adults demonstrated significantly attenuated P600 responses compared to older adults across lateral sites: left anterior (1.056 vs. 5.369 V, $p < 0.001$), left posterior (0.234 vs. 0.995 V, $p < 0.05$), and right central regions (1.327 vs. 3.750 V, $p < 0.05$). Conversely, younger adults exhibited significantly enhanced P600 responses over midline sites: anterior (4.031 vs. 1.916 V, $p < 0.005$) and posterior regions (1.280 vs. -1.375 V, $p < 0.001$). No significant three-way interactions emerged for the P600 component.

In summary, younger adults demonstrated relatively increased word-length effects on both negative deflections in earlier and N400 intervals over midline posterior, whereas older adults demonstrated relatively decreased word-length effects on these negative deflections across the whole brain scalp, with long words eliciting smaller negative responses than short ones. Additionally, long words elicited a larger P600 than short words, but three-way interactions were not persistent in the P600 component.

Discussion

In this study, we examined neural correlates of age differences in word-length effects by co-registering EEG data to oculomotor behavior during free-viewing Chinese reading. Our results of age differences in word length effects were in line with a previous eye-tracking study and provided novel evidence from fixation-related brain potentials. Overall, we replicated older adults' larger word-length effects on viewing time measures such as gaze duration, regression path duration, and total reading time. These age differences in word-length effects can be interpreted as older adults preferring to use character-based strategies for Chinese comprehension (S. Li et al., 2018; Rayner et al., 2009) or needing more effort to decode long words than their younger counterparts. Conversely, electrophysiological analyses failed to demonstrate enhanced word length effects in fixation-related potential data. Older adults displayed significantly reduced word-length sensitivity, indicating potential age-related shifts away from word-based lexical access strategies during processing of extended orthographic strings.

Age-Changes in Early and N400 Word-Length Effects

Our FRP results for young adults were partially in line with previous findings in alphabetic word processing (Loberg et al., 2019; Van Petten & Kutas, 1990). We replicated reliable word-length effects from the earliest time window by observing increased negativity deflections over midline posterior scalp for long words compared to short ones, suggesting they process long words holistically. If larger word-length effects on fixation period for older adults were due to greater effort for decoding longer words holistically, this would parallel larger word-length effects in EEG data. As depicted in Table 4 and Figures 3 and 4, we failed to obtain any evidence supporting older readers having larger word-length effects on either earlier negative deflection or the N400, thus completely denying this account. Contrarily, decreased word-length effects on these brain responses were observed among older participants. Our results are not due to older adults' scaling properties of brain responses or their reduced brain activity (Wlotko et al., 2010). In summary, we revealed qualitative differences between older and young adults and favor the view that older adult readers adopt different mechanisms from young adults when recognizing long words.

Our findings sharpen understanding of language networks in older adults. Some researchers have argued that dynamic retrieval networks are susceptible to age-related decline, whereas lexical-semantic network structures are maintained throughout the adult lifespan (Jongman & Federmeier, 2022; Payne & Federmeier, 2017). In this study, word-length effects were used to tap into language network particularities of older adults. Intriguingly, effects of word length on earlier components over posterior scalp suggested some changes in the lexical-semantic network, whereas decreased effects over anterior scalp may arise from age-related changes in dynamic retrieval networks. These findings resonate with viewpoints that older adults' lexical-semantic networks are less organized, less connected, and less efficient (Krethlow et al, 2020). The interconnected lexical networks for long words are more sensitive to aging than short ones, and/or during the N400 response, older adults have not yet assembled characters of especially long words.

Our findings elucidate age-related shifts in cognitive processing mechanisms during reading comprehension. Converging evidence suggests that older adults demonstrate diminished capacity for context-driven, top-down processing strategies relative to younger adults, instead exhibiting increased reliance on stimulus-driven, bottom-up mechanisms for word identification (DeLong et al., 2012; Payne & Federmeier, 2017; Wlotko et al., 2010). Via visual half-field display procedures, Federmeier and Kutas (2019) established that older adults exhibited no left-hemisphere engagement in top-down, context-based processing, instead manifesting a compensatory transition to bottom-up processing mechanisms lateralized to the right hemisphere. Our results of decreased word-length effects over right hemispheric scalp for older adults resonate with these views. Therefore, a possible neurocognitive reason for the lack of evidence supporting word length effects on word identification among older adults is that they rely more on bottom-up interaction processing of characters for word strategy.

Overall, our earlier FRP results revealed that aging causes a shift from word-based to character-based strategy for decoding Chinese long four-character words in reading. This may be due to older adults' visual declines (Owsley, 2011), inefficient parafoveal processing, and word segmentation (He et al., 2021; Zhang et al., 2019). Another possibility is that global representations in the mental lexicon for long four-character words are degraded, and thus older adults rely more on morpheme representations to recognize them (Zhou & Marslen-Wilson, 2000). This account was supported by our FRP effects over posterior scalp. Moreover, brain aging may be the neural basis for this shift (Federmeier & Kutas, 2019; Jongman & Federmeier, 2022; Payne & Federmeier, 2017). Evidence supporting this comes from findings that decreased word length effects were observed in both language dynamic retrieval and lexical-semantic networks, and that older adults relied on bottom-up right-hemisphere processing producing decreased word length effects.

Non-Aging Changes in P600 Word-Length Effects

The present investigation builds upon existing research by strengthening the empirical foundation and advancing theoretical comprehension of compound word-length phenomena in Chinese reading processes. P600 effects are thought to be functionally associated with integrating semantic information into contextual representation (Aurnhammer et al., 2023; Delogu et al., 2019, 2021). In previous lexical decision studies of alphabetic languages, word-length effects dissipated and were even reversed in later intervals, with long words producing weaker P600 responses (Hauk et al., 2006, 2009). Inconsistent with these findings, we obtained increasing word-length effects over midline posterior from earlier negative deflections to the P600 interval, suggesting more permanent word-length effects for Chinese word processing from pre-lexical processing to context interaction. However, no reliable three-way interactions on P600 suggested that older adults adopt a similar mechanism for integrating word meaning into contextual representation.

In summary, our study presents an intact portrait of word-processing changes with aging. Young Chinese adults used word-based strategy for processing both short and long multiple-character words; however, older readers adopted character-based strategy for decoding four-character words and used similar mechanisms to young adults for integrating word meaning into contextual representation. We demonstrated that characters are an important decoding unit when Chinese people age, thus playing an important role in word decoding. These results demonstrate a shift from word-based to character-based strategy for decoding long words when Chinese people age. These results align with established models of Chinese word recognition that incorporate both constituent character analysis and holistic word processing (Chen et al., 2003; X. Li et al., 2014; X. Li & Pollatsek, 2020; Yan et al., 2006), thereby elucidating mechanisms by which Chinese readers decode compound words during text comprehension.

Limitations

Two limitations should be acknowledged. First, we did not assess whether readers perceive four-character words as complete word units or treat them as two separate two-character words, but FRP data among young adults suggest they treat short and long target words as complete word units. The second limitation is that we co-registered EEG data to the first fixation on the first two characters of four-character words to examine how readers decode long words, thus missing data when the first fixation landed on the last two characters. We did not separate temporal overlap components from different fixation points and did not sort out EEG data of refixations. Future research should address these issues.

Declarations

Data Availability Statement

All data, computational code, and research materials have been made publicly available through the Open Science Framework platform (https://osf.io/wxnk8/). We acknowledge that this investigation was conducted without prior preregistration of the study design, hypotheses, or analytical procedures.

Ethics Approval and Consent to Participate

This investigation was conducted under the research project entitled "Study on the cognitive mechanisms of special population in Chinese reading." Ethical approval was obtained from the Institutional Review Board of the Cognition and Brain Disorders Research Centre at Hangzhou Normal University (Protocol No. 20190408), where all experimental procedures were conducted. The study was performed in accordance with the ethical standards outlined in the Declaration of Helsinki.

Consent for Publication

The data and ideas appearing in this manuscript have not been disseminated at any conference or meeting, posted on a listserv, or shared on a website. We do not borrow materials from other works. We grant exclusive rights to the publisher if the article is accepted for publication in *Journal of Research in Reading.*

Competing Interests

There are no conflicts of interest to declare.

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Figure 1. Examples of the target word manipulation in the experiment

Short target word condition: 整天幻想幸运光顾不如踏踏实实地工作。
English translation: It is better to work hard than to fantasize yourself as a lucky person.

Long target word condition: 整天幻想幸运从天而降不如踏踏实实地工作。
English translation: It is better to work hard than to fantasize yourself as a very lucky person.

Note: The underlined words are the targets; the target will not be underlined during reading.

Figure 2. Interest regions from crossing the dimensions of AntPost (Posterior, Central, and Anterior) and Hemisphere (Right, Midline, and Left)

Figure 3. Grand-averaged waveforms over nine scalp regions for young and old adults (negative voltage plotted upward)

Table 1. Means and standard deviations of word frequency, character frequency, and stroke number for target words

Measure	Short target	Long target
Word frequency	4.82 (3836)	4.82 (1631)
First character frequency	6422 (3195)	2.96 (5.71)
Second character frequency	3041 (2864)	3.38 (3.04)
Third character frequency	5367 (2545)	3.49 (2.73)
Fourth character frequency	—	3.77 (2.94)
First character stroke	5.71 (3.38)	—
Second character stroke	3.04 (3.49)	—
Third character stroke	2.73 (3.77)	—
Fourth character stroke	2.94 (3.38)	—

Note: Standard deviations are given in parentheses.

Table 2. The mean and standard errors of eye tracking measures in the target region

Measure	Short word	Long word	Short word	Long word
	Young Adults		**Old Adults**	
First fixation duration	251 (3)	238 (2)	280 (3)	271 (3)
Skipping probability	21.6 (0.7)	4.0 (0.7)	13.7 (0.8)	5.9 (0.8)
Gaze duration	299 (5)	365 (5)	403 (6)	517 (6)
Refixation probability	15.1 (1.0)	46.9 (1.0)	35.5 (1.1)	68.5 (1.1)
Regression path duration	327 (8)	438 (8)	469 (9)	720 (9)
Regressed out probability	15.4 (0.8)	17.4 (0.8)	11.9 (0.9)	13.0 (0.9)
Total reading time	377 (11)	539 (11)	573 (13)	891 (13)
Regressed in probability	23.6 (0.9)	23.7 (0.9)	22.1 (1.0)	24.6 (1.0)

Note: Time measures are in milliseconds. Standard errors are shown in parentheses.

Table 3. Statistical effects of the linear mixed-effects models for eye tracking measures

Model	Intercept	Group	Word length	Group × Word length
First fixation duration	<.001	<.001	<.001	<.001
Skipping probability	<.001	<.001	<.001	<.001
Gaze duration	<.001	<.001	<.001	<.001

Model	Intercept	Group	Word length	Group × Word length
Refixation probability	<.001	<.001	<.001	<.001
Regression path duration	<.001	<.001	<.001	<.001
Regressed out probability	<.001	<.001	<.001	<.001
Total reading time	<.001	<.001	<.001	<.001
Regressed in probability	<.001	<.001	<.001	<.001

Table 4. F-results of ANOVA analyses as a function of age group, word length, and ROIs

Effect	100-300 ms	300-500 ms	500-800 ms
Group	402.242 (p < 0.001)	96.115 (p < 0.001)	98.173 (p < 0.001)
Length	12.694 (p < 0.001)	11.715 (p < 0.001)	10.682 (p < 0.001)
Group × Length	—	—	—
Group × ROIs	13.257 (p < 0.001)	10.682 (p < 0.001)	—
ROIs × Length	3.064 (p = 0.002)	5.068 (p < 0.001)	2.555 (p = 0.010)
Group × Length × ROIs	2.154 (p = 0.030)	2.421 (p = 0.015)	—

Note: The table shows F values; p values are in parentheses. For all simple effects of group, word length, and their interactions, df = (1, 44). For all simple effects of ROIs and interactions with group and word length, df = (8, 352).

Note: Figure translations are in progress. See original paper for figures.