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Lexical entrenchment and cross-language activation: Two sides of the same coin for bilingual reading across the adult lifespan*

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We used eye movement measures of paragraph reading to examine whether two consequences of bilingualism, namely, reduced lexical entrenchment (i.e., reduced lexical quality and accessibility arising from less absolute language experience) and cross-language activation (i.e., simultaneous co-activation of target- and non-target-language lexical representations) interact during word processing in bilingual younger and older adults. Specifically, we focused on the interaction between word frequency (a predictor of lexical entrenchment) and cross-language neighborhood density (a predictor of cross-language activation) during first- and second-language reading. Across both languages and both age groups, greater cross-language (and within-language) neighborhood density facilitated word processing, indexed by smaller word frequency effects. Moreover, word frequency effects and, to a lesser extent, cross-language neighborhood density effects were larger in older versus younger adults, potentially reflecting age-related changes in lexical accessibility and cognitive control. Thus, lexical entrenchment and cross-language activation multiplicatively influence bilingual word processing across the adult lifespan.

Keywords: reading, eye movements, lexical entrenchment, cross-language activation, aging

Central to the study of bilingualism is determining how knowledge and use of two (or more) languages impact how words are represented and accessed from memory during first-language (L1) and second-language (L2) processing. In particular, bilingualism entails two important and potentially interrelated consequences for word processing. First, bilingualism entails reduced lexical entrenchment; bilinguals have less absolute experience with each of their languages than monolinguals, who, by definition, have experience with one language only, leading to reduced lexical quality and accessibility. As well, bilinguals generally have less absolute L2 than L1 experience, leading to reduced lexical quality and accessibility during L2 versus L1 processing (reviewed in Titone, Whitford, Lijewska & Itzhak, 2016; Whitford, Pivneva & Titone, 2016). Second, bilingualism entails cross-language activation; there is consensus that bilinguals have an integrated lexicon, wherein both their languages are concurrently represented, leading to the simultaneous co-activation of target- and non-target-language lexical representations during L1 and L2 processing. Cross-language activation can facilitate or inhibit lexical accessibility, depending on the nature of the task, nature of the cross-language overlap, and current target language (reviewed in de Groot, 2011; Kroll, Gullifer & Zirnstein, 2016; Lauro & Schwartz, 2017; Titone et al., 2016; Van Assche, Duyck & Hartsuiker, 2012; Whitford et al., 2016).

Within this view, both lexical entrenchment and cross-language activation influence how bilinguals represent and access words during L1 and L2 processing. However, open questions are whether these factors additively or multiplicatively influence bilingual word processing, and whether their influence is consistent across the adult lifespan. Prior work by Diependaele, Lemhöfer and Brysbaert (2013) casts lexical entrenchment and cross-language activation as having distinct mechanisms, with potentially independent influences on bilingual word processing (detailed below). However, recent work from

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our group (Whitford et al., 2016) suggests that these factors may not be as theoretically and empirically distinct as Diependaele and colleagues (2013) report (detailed below). In this paper, we use eye movement measures of paragraph reading to examine whether lexical entrenchment (predicted by the effects of word frequency) and cross-language activation (predicted by the effects of cross-language neighborhood density) additively or multiplicatively influence word processing in demographically and linguistically matched bilingual younger (i.e., 18–30 years) and older (i.e., 60+ years) adults. In what follows, we review the relevant literature, and then present the current study.

Lexical entrenchment studies of bilingual word recognition

Lexical entrenchment can be assessed through the word frequency effect, which reflects how easily a word can be identified. The standard finding is that high-frequency words (e.g., *home*) are recognized more easily and more rapidly than low-frequency words (e.g., *kelp*); this finding is indexed by more skipping, shorter fixations, and fewer regressions in the eye movement record (reviewed in Rayner, 1998, 2009; Rayner, Pollatsek, Ashby & Clifton, 2012; Titone et al., 2016; Whitford et al., 2016). Word frequency effects are often regarded as a signature of lexical access, and reflect important structural properties of the mental lexicon (Rayner, 1998, 2009).

According to leading models of bilingual word recognition, such as the *Bilingual Interactive Activation Plus Model* (BIA+, Dijkstra & Van Heuven, 2002) and *Weaker Links Hypothesis* (Gollan, Slattery, Goldenberg, Van Assche, Duyck & Rayner, 2011; Gollan, Montoya, Cera & Sandoval, 2008), low-frequency words, which, by definition, are encountered less often than high-frequency words, have lower baseline activation levels and/or weaker links between word-related information (e.g., orthography, phonology, semantics), leading to reduced lexical quality and accessibility (see also Andrews & Hersch, 2010; Kuperman & Van Dyke, 2013; McClelland & Rumelhart, 1981; Monsell, 1991; Perfetti, 2007; Perfetti & Hart, 2002; Seidenberg & McClelland, 1990, for similar accounts from the monolingual word recognition literature). Moreover, because bilinguals have less absolute experience with each of their known languages than monolinguals, and because bilinguals generally have less absolute L2 than L1 experience, these models predict that their words have lower baseline activation levels and/or weaker links (especially lower-frequency L2 words), leading to larger word frequency effects.

Some of these models also predict age differences in lexical entrenchment; bilingual older adults have accumulated more life-long language experience than bilingual younger adults, and thus, their words should have higher baseline activation levels and/or stronger links, leading to smaller word frequency effects (see Gollan et al., 2008). Although older adults' lexical representations have benefited from more life-long experience, older adults also experience normal age-related cognitive and sensory decline, including reduced inhibition (e.g., Darowski, Helder, Zacks, Hasher & Hambrick, 2008; Hasher, Zacks & May, 1999; Salthouse & Meinz, 1995); reduced working memory (e.g., Bopp & Verhaeghen, 2005; Carpenter, Miyake & Just, 1994; Hasher & Zacks, 1988; Salthouse & Meinz, 1995); reduced processing speed (e.g., Salthouse, 1992, 1996; Salthouse & Meinz, 1995); and reduced visual acuity (reviewed in Fozard & Gordon-Salant, 2001). These factors could outweigh any experience-related linguistic advantages, leading to reduced efficiency in accessing lexical representations, and consequently, larger word frequency effects.

Consistent with this conjecture, a number of studies from the monolingual eye movement literature have reported larger word frequency effects in older versus younger adults during natural reading; this finding is driven by their slower processing of low-frequency words (e.g., Kliegl, Grabner, Rolfs & Engbert, 2004; Laubrock, Kliegl & Engbert, 2006; Rayner, Reichle, Stroud, Williams & Pollatsek, 2006). We note, however, that age differences in word frequency effects can vary across studies as a function of participant characteristics, such as language ability or print exposure (e.g., Payne, Gao, Noh, Anderson & Stine-Morrow, 2012; Stine-Morrow, Soederberg Miller, Gagne & Hertzog, 2008). They can also vary across studies as a function of methodological characteristics, such as reading disappearing or unspaced text (e.g., McGowan, White, Jordan & Paterson, 2014; McGowan, White & Paterson, 2015; Rayner, Yang, Castelhano & Liversedge, 2011; Rayner, Yang, Schuett & Slattery, 2013); making lexical decisions to isolated words (e.g., Allen, Madden, Weber & Groth, 1993; Bowles & Poon, 1981; Tainturier, Tremblay & Lecours, 1989); naming isolated words (e.g., Spieler & Balota, 2000), and so forth.

The literature on lexical entrenchment in bilinguals has provided some support for models of bilingual word recognition. The key findings from studies using eye movement recordings (e.g., sentence, paragraph, and novel reading) are threefold. First, word frequency effects are comparable in monolingual and bilingual younger adults during L1 (or dominant-language) reading (Cop, Keuleers, Drieghe & Duyck, 2015; Gollan et al., 2011). Second, word frequency effects are larger during L2 versus L1 reading among bilingual younger (Cop et al., 2015; Whitford et al., 2016; Whitford & Titone, 2012, 2017) and older (Whitford & Titone, 2017) adults. Third, word frequency effects are larger in bilingual older versus younger adults during both L1 and L2 reading,

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suggesting that normal age-related cognitive and sensory decline may indeed outweigh any experience-dependent advantages in word recognition (Whitford & Titone, 2017). There is also some evidence that both L1 and L2 word frequency effects are sensitive to individual differences in current L2 knowledge and use among bilingual younger adults (Whitford & Titone, 2012, 2017; cf. Cop et al., 2015; Gollan et al., 2011); greater current L2 experience increases L1 word frequency effects, but decreases L2 word frequency effects (see also Whitford & Titone, 2015, 2016, for a similar trade-off in text-level aspects of reading performance). This trade-off, however, does not extend to bilingual older adults (Whitford & Titone, 2017); their L1 and L2 lexical representations have benefited from 60+ years of experience, and thus, may have reached a functional ceiling, rendering them relatively insensitive to graded differences in current L2 experience.

Similar findings have also been reported in studies using response-based tasks (e.g., lexical decision, progressive demasking), and have additionally found that word frequency effects are larger in bilinguals versus monolinguals during L2 processing (e.g., Brysbaert, Lagrou & Stevens, 2016; de Groot, Borgwaldt, Bos & van den Eijnden, 2002; Diependaele et al., 2013; Duyck, Vanderelst, Desmet & Hartsuiker, 2008; Gollan et al., 2011; Lemhöfer, Dijkstra, Schriefers, Baayen, Grainger & Zwisterlood, 2008). These studies, however, have yet to examine age-related differences in word frequency effects.

To summarize thus far, the above-reviewed studies suggest that lexical entrenchment is comparable in monolinguals and bilinguals during L1 processing, but reduced during L2 processing; lexical entrenchment is reduced during L2 versus L1 processing among bilinguals (irrespective of age); and lexical entrenchment is reduced in bilingual older versus younger adults (irrespective of language) – providing some support for models of bilingual word recognition. Thus, the amount of language experience, as well as age-related changes in cognitive and sensory processing, may mediate ease of bilingual word recognition. Recent response-based work by Diependaele and colleagues (2013), which re-analyzed data derived from a progressive demasking task (see Lemhöfer et al., 2008), found that language experience alone (indexed by proficiency on a vocabulary measure) was needed to account for larger bilingual-L2 versus monolingual-L1 word frequency effects. In other words, the authors found that cross-language competition was not necessary to explain reduced lexical accessibility in bilinguals versus monolinguals. However, the authors did not assess L1 processing in their bilinguals, and thus, cannot adjudicate whether lexical entrenchment and cross-language activation additively or multiplicatively impact L1 and L2 word processing among bilinguals.

Cross-language activation studies of bilingual word recognition

Cross-language activation (in the context of word recognition) is usually measured by comparing how bilinguals process words that share lexical characteristics across their languages versus language-unique control words. Words with between-language lexical overlap include *cognates*, which share both orthography and semantics across languages (e.g., <*piano*> is an instrument in both English and French), and *interlingual homographs*, which share orthography, but not semantics across languages (e.g., <*chat*> is a conversation in English vs. cat in French). Studies involving both eye movement recordings and response-based tasks have generally reported facilitatory effects for cognates, and inhibitory effects for interlingual homographs (reviewed in de Groot, 2011; Kroll et al., 2016; Titone et al., 2016; Van Assche et al., 2012; Whitford et al., 2016).

However, a more conservative measure of cross-language activation (in the context of word recognition) would involve words with language-unique representations, as is the case with orthographic neighbors. The classic definition of an orthographic neighbor, now referred to as a *substitution neighbor*, is any word that differs from a target word by a single letter only, while maintaining the total number of letters (Coltheart, Davelaar, Jonasson & Besner, 1977). For example, the English word *road* has the following within-language (English) substitution neighbors: *read; load; toad; roar;* and *roam,* and the following between-language (French) substitution neighbor: *rond.* A more recent definition of an orthographic neighbor includes substitution neighbors, as well as *addition* and *deletion neighbors*, which are created by adding and deleting one letter from a target word, respectively (Davis, Perea & Acha, 2009). For example, the English word *road* has the following within-language (English) addition and subtraction neighbors: *broad* and *roads*; *rod* and *rad*, but no such between-language (French) neighbors. A target word's total number of neighbors is called its *neighborhood density,* and the average word frequency of its neighbors is called its *neighborhood frequency.*

According to leading models of bilingual word recognition, such as BIA+ (Dijkstra & Van Heuven, 2002), whenever bilinguals encounter a word both within- and cross-language orthographic word forms are simultaneously co-activated via spreading activation during bottom-up processing; this activation varies as a function of their orthographic overlap and baseline activation levels. Because lower-frequency and L2 words are generally encountered less often than higher-frequency and L1 words, they should have lower baseline activation levels. BIA+ has yet to simulate neighborhood density effects; however, based on simulations from its predecessor, the *Bilingual Interactive Activation Model*

(BIA, Dijkstra & Van Heuven, 1998), it would likely predict largely inhibitory within- and cross-language neighborhood density effects. Due to lateral inhibition at the lexical level, words with many neighbors should be inhibited by the co-activation of orthographically-similar, yet competing word forms (i.e., neighbors), resulting in delayed lexical accessibility, and ultimately, larger word frequency effects. Lateral inhibition should be especially pronounced for lower-frequency and L2 words; such words have lower baseline activation levels, and thus, would require more time to surpass the co-activation of their neighbors (especially if they are of higher frequency).

Moreover, both BIA and BIA+ have yet to simulate age differences in neighborhood density effects. However, they would potentially predict smaller (albeit inhibitory) within- and cross-language neighborhood density effects in bilingual older versus younger adults; they have accumulated more life-long language experience, and thus, their words (including lower-frequency and L2 words) should have higher baseline activation levels, rendering them less susceptible to the effects of lateral inhibition.

The literature on cross-language activation (as assessed by neighborhood density effects) has exclusively focused on bilingual younger adults, and provides mixed support for models of bilingual word recognition. To date, only two studies have used eye movement recordings to examine neighborhood density effects in bilinguals. In the first of these studies, Whitford and colleagues (2016) re-analyzed Whitford and Titone's (2012) data, which examined L1 and L2 word frequency effects during paragraph reading in a large sample ($n = 117$) of unbalanced English–French bilinguals. The authors observed facilitatory cross-language neighborhood density effects across the L1 and L2; words with many versus few neighbors were processed more easily, as evidenced by smaller word frequency effects. In particular, lower-frequency L1 and L2 words benefited most from having many neighbors. In contrast, the pattern of within-language neighborhood density effects varied across languages; negligible effects were observed during L1 reading, whereas facilitatory effects were observed during L2 reading. Two caveats, however, are that the authors only examined substitution neighbors and did not control for the potential impact of neighborhood frequency.

In the second of these studies, Dirix, Cop, Drieghe, and Duyck (Experiment 2, in press) re-analyzed Cop and colleague's (2015) data, which examined L1 and L2 word frequency effects during novel reading in unbalanced Dutch–English bilinguals, and whether their L1 word frequency effects differed from an English monolingual control group. Using an updated measure of neighborhood density that also included addition and deletion neighbors (see Davis et al., 2009), the authors observed largely facilitatory cross-language neighborhood density effects during L1 and L2 reading (the effects were rather limited during L1 reading, however); words with many versus few neighbors were processed more easily, as evidenced in the eye movement record. In contrast, the pattern of within-language neighborhood density effects varied across languages; both facilitatory and inhibitory effects were observed during L1 reading (for lower-frequency and higher-frequency words, respectively), whereas facilitatory effects were observed during L2 reading.

In sum, contrary to BIA's predictions, studies of natural reading suggest that the activation of within- and cross-language neighbors largely facilitates word recognition, especially under conditions of low lexical entrenchment (e.g., lower-frequency L2 words). These findings are also inconsistent with the monolingual eye movement literature, where largely inhibitory neighborhood density effects have been reported. For example, Pollatsek, Perea and Binder (Experiment 2, 1999) observed inhibitory effects during sentence reading. However, when the authors controlled for the number of high-frequency neighbors, they observed facilitatory effects during early-stage reading, but inhibitory effects during late-stage reading. This suggests that their participants may have misidentified or misread words on the first pass (see also Gregg & Inhoff, 2016; Perea & Pollatsek, 1998; Slattery, 2009; Warrington, White, & Paterson, 2016; cf. Sears, Campbell & Lupker, 2006).

Related to this point, computational models of eye movements during reading, such as E-Z Reader (e.g., Pollatsek et al., 2006; Rayner, Ashby, Pollatsek & Reichle, 2004) and SWIFT (e.g., Engbert, Nuthmann, Richter & Kliegl, 2005; Laubrock et al., 2006), have yet to simulate bilingual reading (they were implicitly developed for monolingual, native language reading). However, they can account for age-related differences in eye movement reading patterns, and can, theoretically, account for reading patterns in bilinguals. For example, these models posit that lexical access is modulated by a word's familiarity. Given that L2 words are less familiar overall for bilinguals, these models would likely predict larger L2 versus L1 word frequency effects. While these models have yet to simulate neighborhood density effects (for computational convenience, they assume that only target words can be lexically processed), they would likely predict facilitatory effects; activation of orthographically-similar word forms (i.e., neighbors) would likely increase a target word's familiarity, and consequently, its accessibility. This process could potentially occur parafoveally, that is, before the target word is directly fixated.

Studies using response-based tasks (including those that have concurrently collected electrophysiological recordings) have reported a complex pattern of inhibitory, facilitatory, and null within- and cross-language neighborhood density effects (e.g., Beauvillain, 1992; Bijeljac-Babic, Biardeau & Grainger, 1997; de Groot et al., 2002; Dirix et al., Experiment 1, in press; Grainger & Dijkstra, 1992; Grossi, Savill, Thomas & Thierry, 2012; Lemhöfer et al., 2008; Midgley, Holcomb, Van Heuven & Grainger, 2008; Van Heuven, Dijkstra & Grainger, 1998), and thus, provide mixed support for models of bilingual word recognition. Findings often widely vary as a function of the experimental task used (e.g., lexical decision, progressive demasking); the linguistic context of the experiment (instructions and/or stimuli presented in one vs. both languages); and whether neighborhood frequency was controlled for (many studies have found that a higher-frequency neighbor leads to inhibitory neighborhood density effects, as evidenced by longer reaction times and lower accuracy). Moreover, all above-mentioned studies have examined substitution neighbors, except that by Dirix and colleagues (Experiment 1, in press). A complex pattern of neighborhood density effects has also been reported in the monolingual response-based literature (e.g., Andrews, 1989, 1992, 1997; Carreiras, Perea & Grainger, 1997; Coltheart et al., 1977; Duñabeitia, Marín & Carreiras, 2009; Grainger, 1992; Perea & Rosa, 2000; Pollatsek, Perea & Binder, Experiment 1, 1999; Sears, Hino & Lupker, 1995; Snodgrass & Mintzer, 1993), although lexical decision tasks tend to yield facilitatory effects.

We want to highlight here that response-based tasks involve decontextualized stimuli (i.e., single words presented in isolation), as well as explicit behavioural decisions (e.g., yes/no responses to words vs. non-words), which could result in dual-task situations and, ultimately, probe cognitive processes that are not truly reflective of natural reading (reviewed in Rayner, 1998, 2009; Rayner et al., 2012; Titone et al., 2016; Whitford et al., 2016). Indeed, recent work by Kuperman, Drieghe, Keuleers, and Brysbaert (2013) suggests that response-based measures tap into language processes that are not necessarily the same as those involved in natural reading. As such, the literature on bilingual neighborhood density effects would greatly benefit from the use of eye movement recordings, which allow for a naturalistic and temporally-precise measure of early- and late-stage word processing.

The current study

Taken together, several studies have independently examined the influence of lexical entrenchment and cross-language activation on bilingual word recognition. However, Whitford and colleagues' (2016) recent work demonstrates that these factors multiplicatively influence L1 and L2 word recognition in bilingual younger adults; greater within- and cross-language neighborhood density facilitate lexical accessibility. As such, their findings negate the theoretical and empirical contrast pointed out by Diependaele and colleagues (2013) – that lexical entrenchment and cross-language activation can independently influence bilingual word recognition.

Here, we examined whether lexical entrenchment (predicted by the effects of word frequency) and cross-language activation (predicted by the effects of cross-language neighborhood density) additively or multiplicatively influenced word recognition during L1 and L2 paragraph reading in matched bilingual younger and older adults. In doing so, we used an updated measure of neighborhood density, which included substitution, addition, and deletion neighbors (see Davis et al., 2009), and controlled for the potentially confounding effects of neighborhood frequency. We predicted multiplicative effects across the adult lifespan, but larger word frequency and cross-language neighborhood density effects in older adults, given age-related changes in lexical accessibility and cognitive control. Importantly, no prior study has investigated cross-language activation, including the effects of neighborhood density, in bilingual older adults during naturalistic reading. Thus, the current study fills an important gap in the empirical literature. Of note, the current study represents a re-analysis of Whitford and Titone's (2017) data, which examined L1 and L2 word frequency and word predictability effects during paragraph reading in bilingual younger and older adults. As such, the participants and methods are identical across the two studies.

Method

Participants

Participants were 62 French–English bilingual younger adults (aged 19–30) and 62 French–English bilingual older adults (aged 61–87) from the McGill/Montreal community. The age groups were matched on: 1) demographic background; 2) language background and self-reported proficiency, derived from an adaptation of the *Language Experience and Proficiency Questionnaire* (LEAP-Q, Marian, Blumenfeld & Kaushanskaya, 2007); and 3) objective language proficiency, derived from separate, L1 and L2 speeded animacy judgment tasks. For the latter (which was exclusively administered for matching purposes), an L2/L1 proficiency ratio was derived by dividing correct L2 reaction times (RTs) by correct L1 RTs (see Van Assche et al., 2012). Also, an L1/L2 accuracy ratio was derived by dividing L1 accuracy by L2 accuracy. See Table 1 for participant characteristics.

Moreover, both age groups had normal or corrected-to-normal vision, and no self-reported history of speech, hearing, learning, neurological, or psychiatric disorders. All older adults were deemed cognitively healthy, based on their scores on a native language version of the *Montreal Cognitive Assessment* (MoCA, Nasreddine, Phillips, Bédirian, Charbonneau, Whitehead, Collin, Cummings & Chertkow, 2005). All scores were above the 26/30 cut-off, with an average score of 28.24 ($\pm$ 1.36). The study was approved by McGill University's Research Ethics Board.

Table 1. *Participant characteristics.*

	Older adults ($n = 62$) [mean (S.D.)]	Younger adults ($n = 62$) [mean (S.D.)]
Age (years)***	68.55 (5.99)	23.18 (3.46)
Gender (male:female ratio)	21:44	18:44
Education (years)	15.94 (4.04)	15.48 (2.42)
Native language (French:English ratio)	43:19	43:19
Age of L2 acquisition (years)	9.37 (6.45)	8.39 (3.08)
Current language exposure (% time)		
L1	69.16 (21.41)	64.68 (16.07)
L2	30.45 (21.05)	33.92 (16.23)
L1 self-report proficiency measures (1-7)[1]		
Reading ability	7.00 (0.00)	6.92 (0.33)
Writing ability	6.84 (0.50)	6.76 (0.69)
Speaking ability	7.00 (0.00)	6.92 (0.33)
Overall competence	6.95 (0.26)	6.81 (0.54)
L2 self-report proficiency measures (1-7)[1]		
Reading ability	5.51 (1.36)	5.61 (1.14)
Writing ability	5.03 (1.67)	4.95 (1.35)
Speaking ability	5.33 (1.39)	5.10 (1.28)
Overall competence	5.42 (1.22)	5.10 (1.14)
Objective language proficiency measure		
L2/L1 RT ratio	1.07 (0.12)	1.10 (0.15)
L1/L2 Accuracy ratio	1.01 (0.03)	1.02 (0.05)

Note. L2 = second-language; L1 = first-language; RT = reaction time.
[1]Scale ranges from 1 (*beginner*) to 7 (*native-like*)
*** $p < .001$

Materials

Stimuli were target words from four paragraphs, representative of day-to-day reading. Two paragraphs, taken from the Government of Canada's website (http://www.canada.gc.ca/home.html), were news articles about Canadian events (benefits of new transportation infrastructure, effects of a hurricane).[1] The other two paragraphs, taken from the English-Canadian and French-Canadian versions of Wechsler Individual Achievement Test - Second Edition (WIAT-II, Wechsler, 2005), were scientific articles (near-extinction of humpback whales, a naturalist's discovery of dinosaur eggs). These paragraphs have been used in prior work from our group (Libben & Titone, 2009; Titone, Libben, Mercier, Whitford & Pivneva, 2011; Whitford et al., 2016; Whitford & Titone, 2012, 2014, 2017).

The English versions of the paragraphs contained 139, 129, 237, and 264 words, and the French versions contained 167, 167, 284, and 354 words. The words of each paragraph were coded for length, frequency, predictability, within-language neighborhood density and frequency, and cross-language neighborhood density and frequency. English subtitle word frequencies (occurrences per million words) were obtained from the Brysbaert and New (2009) SUBTLEX-US corpus using the *English Lexicon Project* (Balota, Yap, Cortese, Hutchison, Kessler, Loftis, Neely, Nelson, Simpson, & Treiman, 2007), and French subtitle word frequencies (occurrences per million words) were obtained from the *LEXIQUE* database (New, Pallier, Ferrand, & Matos, 2001). Both English and French word predictability values were obtained through cumulative Cloze tasks, wherein a separate sample of 22 native-English speakers and 22 native-French speakers guessed the words of each paragraph (on a word-by-word basis) until the entire text was presented (following Miellet, Sparrow & Sereno, 2007; Whitford & Titone, 2012, 2014, 2017). The Cloze tasks were scored as follows: correct guesses were assigned 1 point, and incorrect guesses were assigned 0 points. Average Cloze probabilities were then computed for each word. Lastly, both neighborhood density and neighborhood frequency values (within- and cross-language) were obtained from the

[1] Canada is an officially bilingual country, and thus, any government-related texts are available in both English and French.

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Cross-Linguistic Easy-Access Resource for Phonological and Orthographic Neighborhood Densities (CLEARPOND, Marian, Bartolotti, Chabal & Shook, 2012). See Tables A1 and A2 of the Appendix for paragraph characteristics.

Apparatus

An EyeLink 1000 desktop-mounted system recorded eye movements at a 1 kHz sampling rate (SR-Research, Ontario, Canada). Viewing was binocular; however, tracking was right-eye monocular. Paragraphs were displayed on a 21-inch ViewSonic CRT monitor, positioned 57 centimeters from participants. Text was displayed in yellow, 14-point Courier New font on a black background using Experiment Builder software (SR-Research, Ontario, Canada). Paragraphs were double-spaced and presented on either 1 or 2 display screens, depending on their length. The display screens had a maximum of 15 lines of text, 66 characters per line, and two characters per 1° of visual angle. Eye movements were calibrated with a 9-point grid, with an average fixation error < 0.5° of visual angle following validation.

Procedure

The task order was as follows: paragraph reading; objective language proficiency measure; and language background questionnaire. For the paragraph reading task, participants were instructed to read naturally and silently for comprehension. Participants read two paragraph versions in English and two in French. As such, participants read two paragraphs in their L1 and two in their L2. Paragraph version (i.e., first, second, third, fourth) and paragraph language (i.e., L1, L2) were counterbalanced across participants. After reading each paragraph, comprehension was assessed through orally-presented, open-ended comprehension questions. Five questions were presented for the first and second paragraphs, and ten for the third and fourth paragraphs. The questions were scored as follows: correct answers were assigned 1 point, approximate answers were assigned 0.5 points, and incorrect answers were assigned 0 points (following Radach, Huestegge & Reilly, 2008).

Results

Reading comprehension performance

T-tests revealed that both age groups' comprehension was significantly lower in the L2 than in the L1 (younger adults: 80 vs. 86%; older adults: 72 vs. 81%; both $ps < .05$), and that older adults' comprehension was significantly lower than that of younger adults across both languages (both $ps < .05$).

Eye movement data

The following exclusions were applied to the data: words at the beginning and end of every line of text; punctuated words; proper nouns; function words; repeated words; and form-identical cross-linguistically ambiguous words, such as cognates and interlingual homographs (see Miellet et al., 2007; Pollatsek, Reichle & Rayner, 2006; Whitford & Titone, 2012, 2014, 2017). This resulted in a total of 311 language-unique target words across all four paragraphs. Moreover, a lower limit of 100 ms (2.88 % of all data) and an upper limit of 5,000 ms (0.43 % of all data) were applied to all fixations. Although an upper limit of 1,000 ms is normally used in eye movement reading research, an upper limit of 5,000 ms was chosen to maximize data inclusion. However, fixations did not exceed 1,820 ms in the analyses.

Both early- and late-stage reading measures were examined, which reflect lexical access and post-lexical integration, respectively (reviewed in Clifton, Staub & Rayner, 2007; Radach & Kennedy, 2013; Rayner, 1998, 2009; Rayner et al., 2012; Titone et al., 2016; Whitford et al., 2016). Early-stage measures included FIRST FIXATION DURATION (i.e., duration of the first fixation on a word) and GAZE DURATION (i.e., sum of all fixation durations on a word during the first pass). Late-stage measures included GO-PAST TIME (i.e., sum of all fixation durations on a word during the first pass and re-fixation durations on earlier occurring words, until a saccade is made to a later occurring word) and TOTAL READING TIME (i.e., sum of all fixation and re-fixation durations on a word).

We used linear mixed models (LMMs) within the lme4 package of R (version 3.3.0) to analyze the data (Baayen, 2008; Bates, 2007; R Development Core Team, 2010). We computed four models for each eye movement measure. Two models examined the interaction between word frequency, cross-language neighborhood density, and age group. Specifically, Model 1 examined the impact of cross-language (L2) neighborhood density on L1 reading (while controlling for L2 neighborhood frequency, as well as L1 neighborhood density), and Model 2 examined the impact of cross-language (L1) neighborhood density on L2 reading (while controlling for L1 neighborhood frequency, as well as L2 neighborhood density). Similarly, two models examined the interaction between word frequency, within-language neighborhood density, and age group. Specifically, Model 3 examined the impact of within-language (L1) neighborhood density on L1 reading (while controlling for L1 neighborhood frequency, as well as L2 neighborhood density), and Model 4 examined the impact of within-language (L2) neighborhood density on L2 reading (while controlling for L2 neighborhood frequency, as well as L1 neighborhood density). We controlled for several other lexical and participant-related variables (detailed subsequently).

Thus, our fixed factors included: word frequency (continuous, linear, and log-transformed to normalize its distribution); cross- or within-language neighborhood density (continuous); and age group (older vs. younger adults; deviation coded: $-0.5, 0.5$). Our control predictors included: within- or cross-language neighborhood density (continuous); cross- or within-language neighborhood frequency (continuous); word length (continuous); word predictability (continuous); participant native language (English vs. French; deviation coded: -0.5, 0.5); and paragraph language version (English vs. French; deviation coded: $-0.5, 0.5$).[2] We scaled (i.e., standardized, z-scored) all continuous variables to reduce collinearity, which was < 0.48 across all models (the highest value was between word frequency and word length). Our random factors included: random intercepts for participants and paragraph version (see Barr, Levy, Scheepers & Tily, 2013; Bates, Kliegl, Vasishth, & Baayen, 2015).[3]

Because we analyzed several eye movement measures, we addressed the potential issue of multiple comparisons (and potentially inflated rates of Type I error) by applying a Bonferroni correction (see von der Malsburg & Angele, 2017). It is unclear, however, whether the results of the simulations reported in that paper extend to more complex designs of the kind reported here, and whether one ought to correct for multiple comparisons across eye movement measures that presumably tap into distinct cognitive processes, such as initial lexical activation versus post-lexical integration. Nonetheless, the α threshold (0.05) was divided by the number of eye movement measures (4), yielding a lowered α threshold (0.0125). This correction was applied to each model/analysis. All significant fixed effects and their interactions ($p < 0.0125$) are first summarized in Tables 2 through 5 (to facilitate ease of data interpretation), and then reported in full. Complete model outputs can be found in Tables A3 through A6 of the Appendix.[4]

2 Given the imbalance between native-French and native-English participants in our study (approximately 2:1), and thus, the L1-L2 contrast for paragraph language version, we included participant native language and paragraph language version as control predictors in our models (see Tables A3 through A6 of the Appendix).

3 The conclusions drawn in the Barr et al. (2013) paper with respect to random slope adjustments technically only apply to designs that include categorical fixed effects. This is because the authors never simulated continuous fixed effects in their paper, and referred to them more generally as covariates. Given this precedent, we did not include random slope adjustments for continuous fixed effects in our models.

4 Although not part of our core analyses, we also analyzed *skipping* (i.e., probability of fixating a word during the first pass) and *regressions out* (i.e., probability of regressing out of a word to an earlier occurring word) to present readers with a more complete picture of participants' eye movement record. As can be seen in Tables A7 and A8 of the Appendix, no age effects nor interactions between word frequency and neighborhood density reached significance.

Table 2. *Overview of significant effects from Model 1.*

	Main Effects			Interactions			
Eye Movement Measure	Frequency	Neighborhood Density	Age	Frequency * Neighborhood Density	Frequency * Age	Neighborhood Density * Age	Frequency * Neighborhood Density * Age
First Fixation Duration	√	X	√	X	X	X	X
Gaze Duration	√	X	√	√	Marginal	X	X
Go-Past Time	√	X	√	X	X	X	X
Total Reading Time	√	√	Marginal	Marginal	√	√	X

Table 3. *Overview of significant effects from Model 2.*

	Main Effects			Interactions			
Eye Movement Measure	Frequency	Neighborhood Density	Age	Frequency * Neighborhood Density	Frequency * Age	Neighborhood Density * Age	Frequency * Neighborhood Density * Age
First Fixation Duration	√	X	√	X	X	X	X
Gaze Duration	√	X	√	√	√	X	X
Go-Past Time	√	X	Marginal	X	X	X	X
Total Reading Time	√	X	√	√	√	X	X

Table 4. *Overview of significant effects from Model 3.*

	Main Effects			Interactions			
Eye Movement Measure	Frequency	Neighborhood Density	Age	Frequency * Neighborhood Density	Frequency * Age	Neighborhood Density * Age	Frequency * Neighborhood Density * Age
First Fixation Duration	√	X	√	X	X	X	X
Gaze Duration	√	√	√	√	Marginal	X	X
Go-Past Time	√	X	√	X	X	X	X
Total Reading Time	√	Marginal	Marginal	√	√	X	X

Table 5. *Overview of significant effects from Model 4.*

	Main Effects			Interactions			
Eye Movement Measure	Frequency	Neighborhood Density	Age	Frequency * Neighborhood Density	Frequency * Age	Neighborhood Density * Age	Frequency * Neighborhood Density * Age
First Fixation Duration	√	X	√	X	X	X	X
Gaze Duration	√	X	√	√	√	X	X
Go-Past Time	√	X	Marginal	X	X	X	X
Total Reading Time	√	X	√	√	√	X	X

We want to highlight here that we originally examined whether individual differences in current L1/L2 experience modulated the interaction between word frequency and neighborhood density; however, there was no impact in either age group, and thus, this factor was removed from the models. This factor did, however, modulate L1 and L2 word frequency effects during early-stage reading (gaze duration) among younger adults only. Specifically, greater current L1 experience led to smaller L1 word frequency effects, whereas greater current L2 experience led to smaller L2 word frequency effects (see Whitford & Titone, 2012, 2016, for similar findings).

Model 1: Impact of cross-language (L2) neighborhood density on L1 reading

Three main effects occurred. First, a significant effect of word frequency was found for all eye movement measures. Specifically, as word frequency increased, first fixation durations ($b = -7.76$, $SE = 1.78$, $t = -6.59$, $p < .001$), gaze durations ($b = -19.97$, $SE = 2.23$, $t = -8.97$, $p < .001$), go-past times ($b = -136.47$, $SE = 14.99$, $t = -9.10$, $p < .001$), and total reading times ($b = -45.94$, $SE = 4.76$, $t = -9.66$, $p < .001$) decreased. Second, a significant effect of cross-language (L2) neighborhood density was found for total reading time. Specifically, as cross-language (L2) neighborhood density increased, total reading times ($b = -15.22$, $SE = 5.37$, $t = -2.83$, $p = 0.005$) decreased. Third, a significant effect of age group was found for all eye movement measures, except total reading time, which was marginal. Specifically, older versus younger adults' first fixation durations ($b = -23.13$, $SE = 5.86$, $t = -3.95$, $p < .001$), gaze durations ($b = -29.75$, $SE = 10.23$, $t = -2.91$, $p = 0.004$), go-past times ($b = -172.43$, $SE = 65.97$, $t = -2.61$, $p = 0.010$), and total reading times ($b = -70.81$, $SE = 31.64$, $t = -2.24$, $p = 0.027$) were longer.[5]

Moreover, three interactions occurred. First, a significant two-way interaction between word frequency and cross-language (L2) neighborhood density was found for gaze duration ($b = 4.63$, $SE = 1.94$, $t = 2.38$, $p = 0.010$), and was marginal for total reading time ($b = 8.71$, $SE = 4.18$, $t = 2.08$, $p = 0.037$). As can be seen in Figure 1, word frequency effects were smaller for high-density versus low-density words.[6] In particular,

[5] All age effects reported in the paper persist even when controlling for general slowing, that is, when analyzing standardized (i.e., z-scored) fixation measures.

[6] Although neighborhood density (fixed effect) was analyzed continuously in all models, it was dichotomized at the median for illustration purposes only. As such, L1 neighborhood density was divided into high-density and low-density words (≥ 3: $n = 165$ words; < 3: $n = 146$ words, respectively), as was L2 neighborhood density (> 0: $n = 124$ words; $= 0$: $n = 187$ words, respectively).

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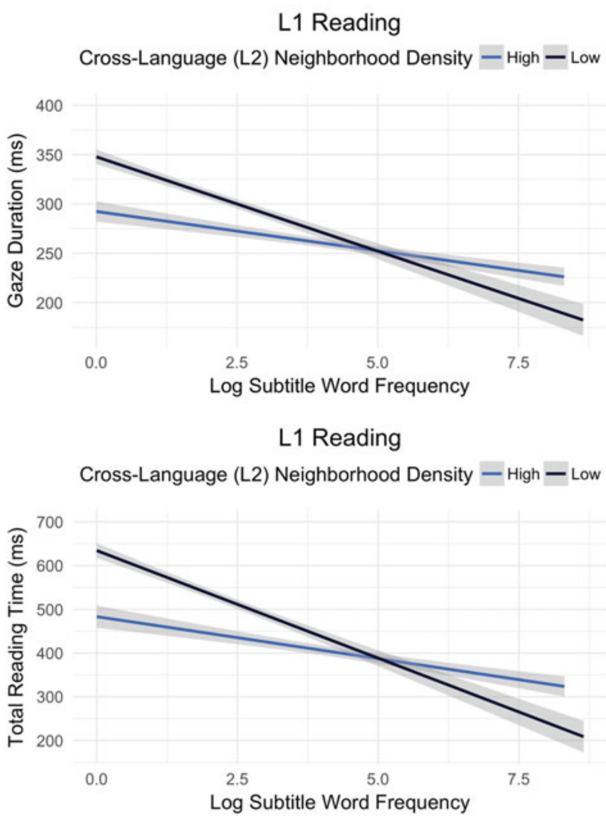

Figure 1. (Colour online) The interaction between word frequency and cross-language (L2) neighborhood density during L1 reading. Actual values are plotted for gaze duration (top panel) and total reading time (bottom panel).

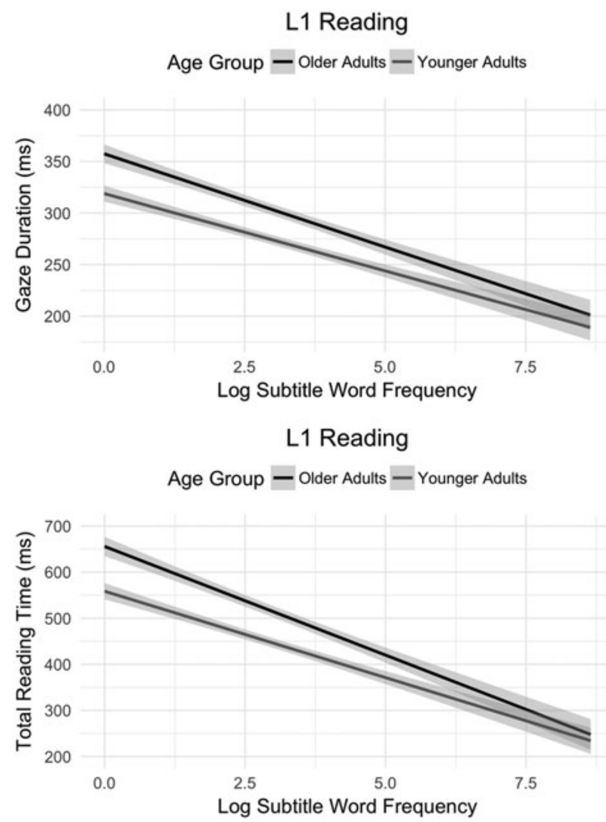

Figure 2. The interaction between word frequency and age group during L1 reading. Actual values are plotted for gaze duration (top panel) and total reading time (bottom panel).

lower-frequency words benefited most from having many cross-language neighbors.

Second, a significant two-way interaction between word frequency and age group was found for total reading time ($b = 22.68$, $SE = 7.73$, $t = 2.93$, $p = 0.003$), and was marginal for gaze duration ($b = 7.92$, $SE = 3.61$, $t = 2.19$, $p = 0.028$). As can be seen in Figure 2, word frequency effects were larger for older versus younger adults. In particular, older adults were differentially slower at processing lower-frequency words.

Third, a significant two-way interaction between cross-language (L2) neighborhood density and age group was found for total reading time ($b = 21.90$, $SE = 8.59$, $t = 2.55$, $p = 0.011$). As can be seen in Figure 3, cross-language (L2) neighborhood density effects were larger for older versus younger adults. In particular, older adults were differentially slower at processing low-density words.

Summary of Model 1 results

We found that greater cross-language (L2) neighborhood density facilitated L1 lexical access and post-lexical integration, indexed by smaller word frequency effects during early- and late-stage reading (across both age groups). We also found that older versus younger adults exhibited reduced L1 lexical entrenchment, indexed by larger word frequency effects during early- and late-stage reading, as well as greater cross-language activation, indexed by larger cross-language (L2) neighborhood density effects during late-stage reading.

Model 2: Impact of cross-language (L1) neighborhood density on L2 reading

Two main effects occurred. First, a significant effect of word frequency was found for all eye movement measures. Specifically, as word frequency increased, first fixation durations ($b = -10.93$, $SE = 1.39$, $t = -7.87$, $p < .001$), gaze durations ($b = -33.49$, $SE = 2.81$, $t = -11.90$, $p < .001$), go-past times ($b = -85.24$, $SE = 16.55$, $t = -5.15$, $p < .001$), and total reading times ($b = -78.52$, $SE = 6.46$, $t = -12.16$, $p < .001$) decreased. Second, a significant effect of age group was found for all eye movement measures, except go-past time, which was marginal. Specifically, older versus younger adults' first fixation durations ($b = -24.53$, $SE = 7.10$, $t = -3.45$, $p < .001$), gaze durations ($b = -35.39$, $SE = 13.47$, $t = -2.63$, $p = 0.010$), go-past times ($b = -154.13$, $SE = 61.22$, $t = -2.52$,

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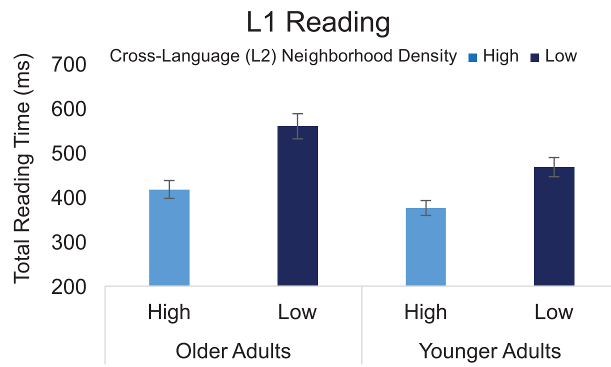

Figure 3. (Colour online) The interaction between cross-language (L2) neighborhood density and age group during L1 reading. Means and standard errors are plotted for total reading time.

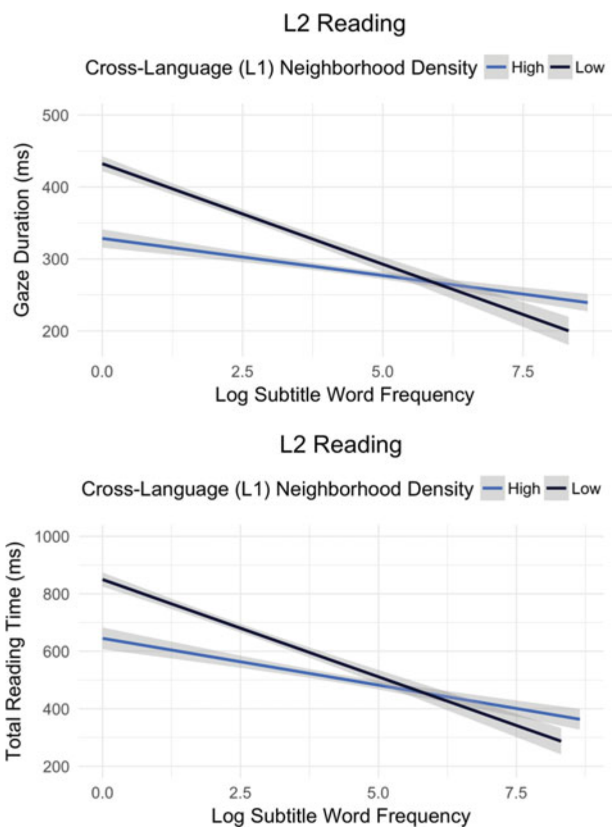

Figure 4. (Colour online) The interaction between word frequency and cross-language (L1) neighborhood density during L2 reading. Actual values are plotted for gaze duration (top panel) and total reading time (bottom panel).

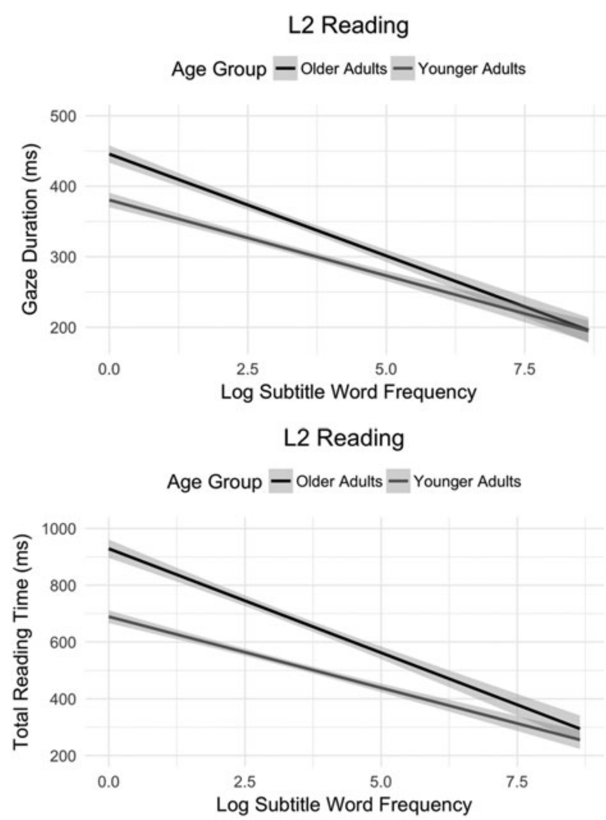

Figure 5. The interaction between word frequency and age group during L2 reading. Actual values are plotted for gaze duration (top panel) and total reading time (bottom panel).

$p = 0.013$), and total reading times ($b = -155.82$, $SE = 44.04$, $t = -3.54$, $p < .001$) were longer.

Moreover, two interactions occurred. First, a significant two-way interaction between word frequency and cross-language (L1) neighborhood density was found for gaze duration ($b = 11.66$, $SE = 2.43$, $t = 4.81$, $p < .001$) and total reading time ($b = 20.97$, $SE = 5.55$, $t = 3.78$, $p < .001$). As can be seen in Figure 4, word frequency effects were, again, smaller for high-density versus low-density words. In particular, lower-frequency words, again, benefited most from having many cross-language neighbors.

Second, a significant two-way interaction between word frequency and age group was found for gaze duration ($b = 12.35$, $SE = 4.79$, $t = 2.58$, $p = 0.010$) and total reading time ($b = 46.70$, $SE = 10.94$, $t = 4.27$, $p < .001$). As can be seen in Figure 5, word frequency effects were, again, larger for older versus younger adults.

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In particular, older adults were, again, differentially slower at processing lower-frequency words.

Summary of Model 2 results

We found that greater cross-language (L1) neighborhood density facilitated L2 lexical access and post-lexical integration, indexed by smaller word frequency effects during early- and late-stage reading (across both age groups). We also found that older versus younger adults exhibited reduced L2 lexical entrenchment, indexed by larger word frequency effects during early- and late-stage reading.

Model 3: Impact of within-language (L1) neighborhood density on L1 reading

Three main effects occurred. First, a significant effect of word frequency was found for all eye movement measures. Second, a significant effect of within-language (L1) neighborhood density was found for gaze duration, and was marginal for total reading time. Third, a significant effect of age group was found for all eye movement measures, except total reading time, which was marginal. Given that these effects are comparable to those reported earlier, they are not further described for the sake of parsimony (see Tables A3 through A6 of the Appendix).

Moreover, two interactions occurred. First, a significant two-way interaction between word frequency and within-language (L1) neighborhood density was found for gaze duration ($b = 11.08$, $SE = 1.86$, $t = 5.94$, $p < .001$) and total reading time ($b = 19.62$, $SE = 4.01$, $t = 4.90$, $p < .001$). As can be seen in Figure 6, word frequency effects were smaller for high-density versus low-density words. In particular, lower-frequency words benefited most from having many within-language neighbors.

Second, a significant two-way interaction between word frequency and age group was found for total reading time, and was marginal for gaze duration. Given that these effects are comparable to those reported earlier, they are not further described for the sake of parsimony (see Tables A4 and A6 of the Appendix).

Summary of Model 3 results

We found that greater within-language (L1) neighborhood density facilitated L1 lexical access and post-lexical integration, indexed by smaller word frequency effects during early- and late-stage reading (across both age groups). We also found that older versus younger adults exhibited reduced L1 lexical entrenchment, indexed by larger word frequency effects during early- and late-stage reading.

Model 4: Impact of within-language (L2) neighborhood density on L2 reading

Two main effects occurred. First, a significant effect of word frequency was found for all eye movement measures.

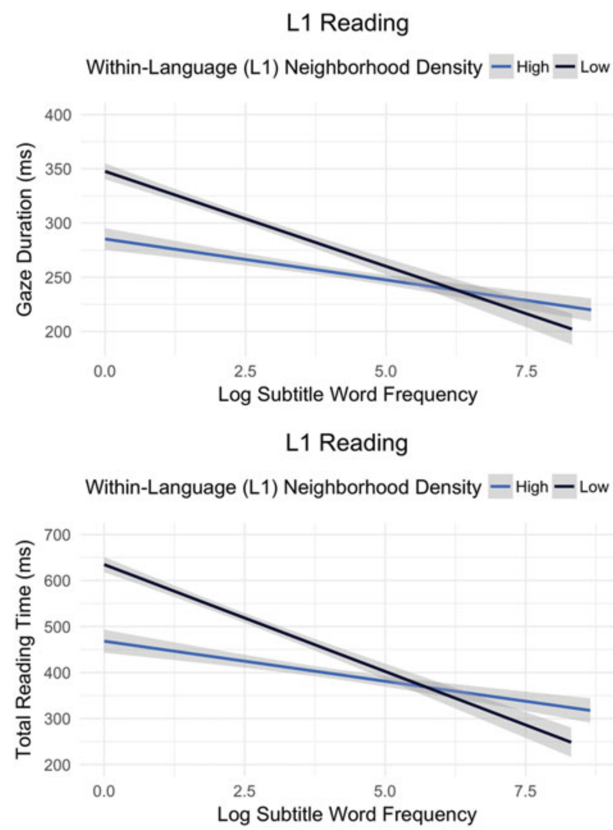

Figure 6. (Colour online) The interaction between word frequency and within-language (L1) neighborhood density during L1 reading. Actual values are plotted for gaze duration (top panel) and total reading time (bottom panel).

Second, a significant effect of age group was found for all eye movement measures, except go-past time, which was marginal. Given that these effects are comparable to those reported earlier, they are not further described for the sake of parsimony (see Tables A3 through A6 of the Appendix).

Moreover, two interactions occurred. First, a significant two-way interaction between word frequency and within-language (L2) neighborhood density was found for gaze duration ($b = 10.47$, $SE = 2.36$, $t = 4.43$, $p = < .001$) and total reading time ($b = 33.61$, $SE = 5.38$, $t = 6.25$, $p < .001$). As can be seen in Figure 7, word frequency effects were, again, smaller for high-density versus low-density words. In particular, lower-frequency words, again, benefited most from having many within-language neighbors.

Second, a significant two-way interaction between word frequency and age group was found for gaze duration and total reading time. Given that these effects are comparable to those reported earlier, they are not further described for the sake of parsimony (see Tables A4 and A6 of the Appendix).

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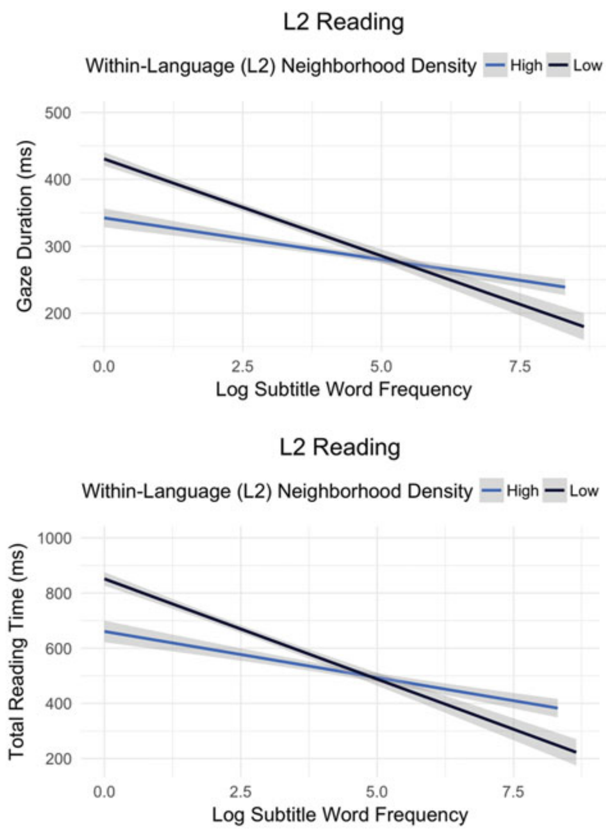

Figure 7. (Colour online) The interaction between word frequency and within-language (L2) neighborhood density during L2 reading. Actual values are plotted for gaze duration (top panel) and total reading time (bottom panel).

Summary of Model 4 results

We found that greater within-language (L2) neighborhood density facilitated L2 lexical access and post-lexical integration, indexed by smaller word frequency effects during early- and late-stage reading (across both age groups). We also found that older versus younger adults exhibited reduced L2 lexical entrenchment, indexed by larger word frequency effects during early- and late-stage reading.

Discussion

Prior response-based work by Diependaele and colleagues (2013) casts lexical entrenchment and cross-language activation as having distinct mechanisms, with potentially independent influences on bilingual word processing. However, in a recent re-analysis of Whitford and Titone's (2012) eye movement data examining L1 and L2 word frequency effects during paragraph reading in a large sample ($n = 117$) of bilingual younger adults, Whitford and colleagues (2016) found that these factors multiplicatively influence bilingual word processing. Given that eye movement measures allow for a highly naturalistic and temporally-sensitive measure of the cognitive processes implicated in reading (reviewed in Rayner, 1998, 2009; Rayner et al., 2012; Titone et al., 2016; Whitford et al., 2016), Whitford and colleagues' (2016) findings likely better capture the dynamics of bilingual word recognition.

In the current study, we re-analyzed Whitford and Titone's (2017) eye movement data examining L1 and L2 word frequency and word predictability effects during paragraph reading in a different sample of matched bilingual younger ($n = 62$) and older ($n = 62$) adults. Our research question was whether lexical entrenchment (predicted by the effects of word frequency) and cross-language activation (predicted by the effects of cross-language neighborhood density) additively or multiplicatively influence bilingual word recognition across the adult lifespan, using an updated measure of neighborhood density (Davis et al., 2009) and controlling for the potentially confounding effects of neighborhood frequency.

Our key findings were threefold. First, across both languages and both age groups, greater within- and cross-language neighborhood density facilitated lexical access and post-lexical integration, indexed by smaller word frequency effects during early- and late-stage reading, respectively. Second, across both languages and both reading stages, word frequency effects were larger in older versus younger adults. Third, cross-language neighborhood density effects were largely age-invariant, although there was some evidence of larger effects in older adults during late-stage L1 reading only. We now further discuss these findings below.

Joint impact of lexical entrenchment and cross-language activation

The first key finding was that lexical entrenchment and cross-language activation jointly influenced bilingual word recognition; greater cross-language neighborhood density facilitated word recognition during early- and late-stage reading (irrespective of language and age), as evidenced by smaller word frequency effects. As such, words were easier to recognize when they had many versus few cross-language neighbors; this was especially true for words suffering from reduced lexical entrenchment (i.e., lower-frequency L1 and lower-frequency L2 words). A similar relationship was also found between word frequency and within-language neighborhood density (again, irrespective of language and age).

Our facilitatory neighborhood density effects do not support models of bilingual word recognition, such as BIA and BIA+ (Dijkstra & Van Heuven, 1998, 2002), which predict lateral inhibition at the lexical level. Accordingly, words with many neighbors should be inhibited by their co-activation, resulting in reduced lexical accessibility, and ultimately, larger word frequency effects. Rather, our findings suggest that the co-activation of neighbors boosts activation of the correct lexical representation (potentially because of feedback activation from comparable letter strings), resulting in increased lexical accessibility, and ultimately, smaller word frequency effects. Given that lower-frequency words benefited most from having large neighborhood densities, one possibility is that such words do not need to be as entrenched as other words to reach activation thresholds, potentially reflecting an activation advantage in the bilingual mental lexicon. Conversely, higher-frequency words do not reap the benefits of large neighborhood densities to the same degree as their lower-frequency counterparts because they do not need to; they are already well-entrenched, and consequently, are easy to activate. We note, however, that BIA and BIA+ were originally developed for single-word recognition during response-based tasks, which, as mentioned earlier, may tap into cognitive processes that are not normally implicated in natural reading. Thus, the models may need to be adjusted to allow for a facilitatory interaction between word frequency and neighborhood density, at least within the context of natural reading.

Although computational models of eye movements during reading, such as E-Z Reader (e.g., Pollatsek et al., 2006; Rayner et al., 2004) and SWIFT (e.g., Engbert et al., 2005; Laubrock et al., 2006), have yet to simulate bilingual reading, the current study may have implications for this area of research. Such models have successfully simulated age differences in the eye movement record, and can, in principle, be extended to reading in bilinguals, both young and old in age. Similar to models of bilingual language processing, these models assume that lexical access is mediated by word-level properties, such as word familiarity, and thus, would likely predict larger L2 versus L1 word frequency effects in our sample of participants (as L2 words are less familiar overall). However, unlike models of bilingual language processing, these models do not assume spreading activation, that is, that target words can co-activate non-target candidates (for further discussion, see Slattery, 2009). Consequently, these models have yet to successfully simulate neighborhood density effects. However, given that lexical access is mediated by word familiarity, which may exert an effect parafoveally before a target word is directly fixated (Inhoff & Rayner, 1986), these models would likely predict facilitatory neighborhood density effects; feedback activation from orthographically-similar word forms would likely increase a target word's familiarity, and consequently, boost its accessibility. Were this conjecture to be supported, it is possible that computational models of reading may be more effective in accounting for bilingual reading effects than more general psycholinguistic models of bilingualism that are not specific to natural reading.

Our findings are largely consistent with two recent eye movement studies examining neighborhood density effects in bilingual younger adults during paragraph (Whitford et al., 2016) and novel (Dirix et al., Experiment 2, in press) reading; facilitatory effects were also reported across both languages and both reading stages. Our findings are, however, largely inconsistent with studies from the monolingual eye movement literature (which can be regarded as investigations of within-language neighborhood density effects); inhibitory effects were reported during early- and late-stage sentence reading (e.g., Perea & Pollatsek, 1998; Pollatsek et al., Experiment 2, 1999; Slattery, 2009). Interestingly, however, when these studies controlled for the number of high-frequency neighbors, facilitatory effects emerged during early-stage reading, but inhibitory effects persisted during late-stage reading. This suggests that monolingual younger adults were misreading target words as their higher-frequency neighbors on the first pass (see also Gregg & Inhoff, 2016; Warrington et al., 2016). However, we did not observe inhibitory effects during late-stage reading in the current study – this finding, in conjunction with our participants' relatively high comprehension scores, suggests that our participants were unlikely misreading words on the first pass. We say "relatively high" because we did not use simple yes/no questions to assess comprehension, but rather, open-ended questions. Thus, both our reading task and comprehension questions were more cognitively demanding than what is typically used in eye movement studies of sentence reading, which likely contributed to the lower levels of reading comprehension. Moreover, these differences also suggest that findings from eye movement studies involving monolinguals may not generalize to reading behavior in bilinguals.

Lastly, given the complex pattern of inhibitory, facilitatory, and null neighborhood density effects reported in the bilingual (e.g., Beauvillain, 1992; Bijeljac-Babic et al., 1997; de Groot et al., 2002; Dirix et al., Experiment 1, in press; Grainger & Dijkstra, 1992; Grossi et al., 2012; Lemhöfer et al., 2008; Midgley et al., 2008; Van Heuven et al., 1998) and monolingual (Andrews, 1989, 1992, 1997; Carreiras et al., 1997; Coltheart et al., 1977; Duñabeitia et al., 2009; Grainger, 1992; Perea & Rosa, 2000; Pollatsek et al., Experiment 1, 1999; Sears et al., 1995; Snodgrass & Mintzer, 1993) response-based word recognition literatures, we deduce that the nature of neighborhood density effects may be task-specific outside the context of natural reading, but largely facilitatory within the context of natural reading.

Impact of age on lexical entrenchment

The second key finding was that word frequency effects were larger in older versus younger adults (irrespective of language and reading stage), and driven by differentially

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slower processing of lower-frequency words (even when controlling for age-related slowing). This finding suggests that normal age-related cognitive (e.g., working memory, inhibition) and sensory (e.g., visual acuity) decline may outweigh any experience-dependent advantages in word processing, leading to reduced lexical entrenchment.

This finding is inconsistent with models of bilingual word recognition, such as BIA+ and the Weaker Links Hypothesis, which predict smaller word frequency effects with increased age; greater life-long language experience should result in higher baseline activation levels and/or stronger links, and consequently, smaller word frequency effects (Dijkstra & Van Heuven, 2002; Gollan et al., 2008, 2011). However, we, again, note that these models were originally developed for single-word recognition during response-based tasks, and thus, may not fully account for the greater cognitive and sensory processing demands associated with more contextualized reading (which may be especially heightened with increased age).

This finding is, however, consistent with prior work from the monolingual eye movement literature, which has also reported some evidence of larger word frequency effects among older adults during naturalistic reading (e.g., Kliegl et al., 2004; Laubrock et al., 2006; Rayner et al., 2006). Thus, older adults may experience age-related difficulties with initial word activation during reading, despite having accumulated more absolute experience with words. However, another view advanced by Spieler and Balota (2000) is that older adults' greater absolute experience with words promotes *unitization*, that is, processing driven by integrated word representations (predicted by larger lexical effects, such as word frequency) rather than component word features (predicted by smaller sublexical effects, such as neighborhood density). While we find evidence of larger word frequency effects in our sample of older adults, we do not find evidence of smaller neighborhood density effects. To the contrary, cross-language neighborhood density effects were either age-invariant or larger in our sample of older adults – a point which we further discuss below.

Impact of age on cross-language activation

The third key finding was that within- and cross-language neighborhood density effects were largely age-invariant, although there was some evidence of larger effects in older adults during late-stage L1 reading only. Intuitively, this latter finding suggests that age-related decrements in cognitive control (e.g., inhibition) results in greater cross-language activation of orthographically-similar word forms. However, we did not find evidence of reduced cognitive control in our sample of older adults. As part of a larger experimental protocol, our participants were administered an executive function battery that included non-linguistic Simon and Stroop tasks, measures of inhibitory control (for detailed descriptions, see Blumenfeld & Marian, 2011). Interestingly, we found that difference scores (i.e., accuracy for inconsistent trials minus accuracy for consistent trials) did not significantly differ between older and younger adults (Simon: M_{Older} = 38.21% vs. $M_{Younger}$ = 38.66%, $p = 0.96$; Stroop: M_{Older} = 26.93% vs. $M_{Younger}$ = 29.65%, p = 0.83). These findings contrast with prior work from the monolingual response-based literature, which has reported larger neighborhood density effects in older versus younger adults during spoken word recognition; these effects also negatively correlated with performance on a Stroop task (Sommers, 1996; Sommers & Danielson, 1999; cf. Spieler & Balota, 2000). Thus, our largely age-invariant findings may indeed be driven by relatively preserved inhibitory control in our sample of older adults (see, for example, Bialystok & Craik, 2010; Bialystok, Craik, & Luk, 2008; Grady, Luk, Craik, & Bialystok, 2015, for other reports of preserved inhibitory control in bilingual older adults).

Conclusion

The current study fills an important gap in the bilingualism literature by demonstrating that lexical entrenchment (as predicted by the effects of word frequency) and cross-language activation (as predicted by the effects of cross-language neighborhood density) interactively constrain word recognition in bilingual adults, regardless of age. As such, these factors may indeed reflect two sides of the same coin for bilingual reading across the adult lifespan. Future research should explore how leading models of bilingual language processing, such as BIA+ (Dijkstra & Van Heuven, 2002) and the Weaker Links Hypothesis (Gollan et al., 2008, 2011), can be modified to account for the impact of these (and other) lexical variables within the context of natural reading, and potentially integrated with leading models of eye movement control during reading, such as E-Z Reader (e.g., Pollatsek et al., 2006; Rayner et al., 2004) and SWIFT (e.g., Engbert et al., 2005; Laubrock et al., 2006). Such work would elucidate how language and oculomotor control processes interact to subserve reading in bilingual younger and older adults.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1366728917000554

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