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Stimulus intelligibility impacts L1 effects on L2 visual word recognition

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A B S T R A C T

For bilinguals, lexical knowledge in the native language (L1) influences word recognition in the second language (L2). When words share both form and meaning across languages, L2 visual word recognition is typically faster, a phenomenon known as the cognate facilitation effect. Such crosslinguistic lexical interaction effects have informed bilingual word recognition models that posit nonselective lexical activation across languages. However, debate remains about the automaticity of this L2-L1 coactivation. The present study examines how the intelligibility of the orthographic input, manipulated through the addition of noise or a difficult font, affects crosslinguistic lexical interactions in Spanish English (L1 L2) bilinguals. The extent to which task difficulty modulates L2-L1 crosslinguistic interactions speaks to different models of bilingual visual word recognition. Experiments 1 shows that stimulus intelligibility attenuates cognate effects. Experiment 2 shows that modulation of cognate effects are partly due to crosslinguistic lexical competitors that is exacerbated by noise. Taken together, Experiments 1 and 2 highlight the importance of simultaneously considering multiple crosslinguistic lexical effects to assess language co-activation. Overall, the findings demonstrate that even under conditions of reduced intelligibility, there is evidence for automatic L2-L1 lexical co-activation.

Reading is an essential skill that facilitates access to linguistic information through vision even for mundane daily tasks. For bilinguals, the knowledge of two languages affects many processes involved in reading including the ability to recognize words. In particular, crosslinguistic influences of word-form similarity (both orthographic and phonological) have greatly influenced the development of models of bilingual visual word recognition. However, until now studies have mostly explored these crosslinguistic effects on visual word recognition using clearly presented standardized text. Yet, decoding a written message does not always involve the typical standardized clear font found in textbooks. In some contexts, the information is more difficult to decipher and less intelligible. For example, in a traditional classroom, hand-written information of varying levels of intelligibility may be presented on a blackboard or smartboard. The current study considers the impact of stimulus intelligibility on visual word recognition, in the context of a bilingual system. Through different manipulations that affect the perceptual clarity of the visual input, this study tests how

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reduced intelligibility affects cross-linguistic lexical co-activation, providing insight into how bilinguals map sensory input onto lexical representations during visual word recognition.

Research that dates back more than 30 years has consistently shown a crosslinguistic effect at the lexical level for clearly presented written words. Shared form and meaning between a word in a second language (L2) and the native language (cognates) facilitates visual word recognition performance (e.g, Dijkstra & Kroll, 2005; Dijkstra et al., 1999, 1998, 2002a). Conversely, L2 words that share form but do not share meaning across the two languages (i.e., false cognates/interlingual homographs) or that share partial form but not meaning (crosslinguisitc neighbors) impair visual word recognition performance (Lemhöfer & Dijkstra, 2004; Dijkstra et al., 1999). Both effects have been taken as evidence that crosslinguistic lexical interactions are automatic during bilingual word recognition, playing an important role in the development of models of bilingual word recognition. Moreover, interactive models of bilingual word recognition propose that the cognate facilitation effect reflects top-down lexical–semantic feedback that enhances activation of shared form representations across languages.

In response to this special issue's call to engage with a chapter from *Cognitive Processing in Bilinguals* (1992), the present study draws on the theoretical foundations outlined by Grainger and Dijkstra (1992). Their chapter captures early perspectives on crosslinguistic lexical interactions derived from findings on cognate and orthographic neighborhood density effects (Harris, 1992). Thirty years later, the current study revisits these ideas by examining cross-linguistic lexical effects on visual word recognition under conditions of perceptual noise. In particular, we highlight how more recent models inspired by the original BIA, including BIA+ and Multilink (Dijkstra et al., 2019; Dijkstra & Van Heuven, 1998, pp. 189–225; Dijsktra & van Heuven, 2002), combined with current views on visual word processing pathways (e.g., dual-route or logogen) (Coltheart et al., 2001; Morton, 1969), led us to test specific predictions for effects of noise on cognate facilitation and crosslinguisitc neighbhoorhood density effects that result from L2-L1 lexical-lexical interactions.

To link influences of noise on early perceptual encoding and subsequent bilingual lexical dynamics, established models of visual word recognition can be a reference for visual stimulus manipulation effects on orthographic activation. Many neuroanatomical and computational models of reading propose an interactive hierarchy in which orthographic information activates phonological and semantic levels (e.g., Coltheart et al., 2001; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Perceptual noise or other visual manipulations that affect stimulus intelligibility reduce the activation of orthographic information, and have a cascading effect on activation levels throughout the language hierarchy. In addition, the increased ambiguity caused by noise reduces the ability to distinguish among orthographically or phonologically similar words increasing lexical competition. Thus lexical-specific characteristics (e.g, word frequency, neighborhood density) (Becker, 1979; Brysbaert et al., 2018; Clark et al., 2021; Gao et al., 2008; Grainger, 1990) should also modulate word recognition performance, and interact with intelligibility. If indeed both languages are activated at an early stage as proposed by BIA+ and Multilink, effects of noise should also modulate crosslinguistic lexical interactions that result from orthographic similarity.

Although a formal neuroanatomical model of bilingual word recognition has not been established, models of monolingual word recognition can be readily adapted to accommodate non-selective bilingual models. A recent neuroimaging study showed that crosslinguistic lexical interaction effects on *auditory* word recognition were exaggerated by auditory noise (Guediche et al., 2023) activating a network of brain areas implicated in cognitive control and lexical selection (Guediche et al., 2021), including regions also implicated in bilingual language control (Abutalebi & Green, 2008; Peeters et al., 2019). The results mirror findings from monolingual listeners showing that perceptual noise increases lexical competition and places greater demands on lexical selection mechanisms (Vaden et al., 2013). Complementary behavioral work tested the prediction that noise increases crosslinguistic lexical competition for translation equivalents with high phonological neighborhood densities (Guediche et al., 2023). The primary goal of the current study is to determine whether visual manipulations that affect stimulus intelligibilty similarly increase crosslinguistic lexical interaction effects on visual word recognition.

To this end, two experiments investigate the effect of intelligibility on crosslinguistic effects: Experiment 1 uses a standard and uniform white noise degradation and examines its impact on the well-established cognate effect. Experiment 2 builds on Experiment 1 and tests a more ecological visual intelligibility manipulation, resembling handwriting. The goal is to determine whether effects of noise on crosslinguistic lexical competition for cognates compared to non-cognates extend to other visual manipulations that affect stimulus intelligibility. Taken together, the studies speak to potential differences among models of bilingual visual word recognition that have historically played a pivotal role in bilingual visual word recognition including the original bilingual interactive activation (BIA) model and the more updated version BIA+, as well as Multilink. Moreover, this study merges areas of research on early visual perceptual processes with downstream effects on bilingual lexical activation, for the first time.

1. Experiment 1

In monolinguals, visual noise and other visual manipulations such as crowding, masking, and font difficulty impair performance on tasks that tap into orthographic lexical processing (e.g, lexical decision) (Barnhart & Goldinger, 2010; Gao et al., 2008; Montani et al., 2015). This is partly due to lexical competition effects which are depicted in interactive models of reading through inhibitory lateral lexical-lexical interactions (e.g, Harm & Seidenberg, 2004; Levy, 1981; McClelland & Rumelhart, 1981). Similarly, in interactive models of bilingual visual word recognition such as BIA (Dijkstra & Van Heuven, 1998, pp. 189–225; Dijkstra and Van Heuven, 1998) and BIA+ (Dijkstra & Van Heuven, 2002), words that overlap in orthographic form across languages compete with one another (Dijkstra et al., 2010; Dijkstra & Kroll, 2005) and impair performance on L2 word recognition tasks, especially in less proficient bilinguals (Van Heuven et al., 1998). In contrast, cognate words which overlap in orthographic form and *also* share meaning ("café"/Spanish, "coffee"/English) are typically recognized faster than non-cognates, especially when the target language is the second non-dominant language. According to ‘interactive’ models of word recognition, the shared meaning boosts activation of the target's overlapping word form, benefiting word recognition. Although BIA and BIA+ (Dijkstra & Van Heuven, 1998, pp. 189–225; Dijkstra and Van Heuven, 2002) do not include a semantic level, Multilink incorporates a language-independent semantic system (Dijkstra et al., 2019). In addition, both BIA+ and Multilink also include a task level system that is not language-specific and would be affected by noise in a non-language specific manner, as well. This task level is not incorporated in the original BIA model.

To our knowledge, none of the existing computational models of bilingual lexical processing have explicitly tested effects of visual noise on cognate facilitation. In the context of an interactive framework, noise should also impact *crosslinguistic* lexical-lexical interactions and modulate visual word recognition performance (e.g, Van Heuven et al., 1998). Therefore, Experiment 1 tests the effects of noise on the cognate effect. Noise also has more global effects on overall task demands increasing effortful processing and influencing decision criteria (Eriksen & Schultz, 1979; Estes, 1972; Ratcliff, 2001).

Effects on decision making seem to depend on the presentation sequence of the noisy stimuli with random presentation of *intermixed* noisy trials producing more detrimental effects on overall word recognition performance than blocked trials (Coles et al., 1985; Eriksen & Schultz, 1979). Accordingly, intermixed sequences should show an effect of task difficulty (Coles, Grafton et al., 1985). The task-level system in BIA+, which was not part of the BIA model, does not feed backwards to impact lexical activation. In the absence of feedback, effects of noise that operate more globally on task difficulty would not then produce additional modulation of crosslinguistic effects. To this end, Experiment 1 explores the impact of noise on cognate effects as a function of the presentation sequence of the noisy stimuli (blocked vs. intermixed).

In this experiment, we also concurrently manipulated the word frequency of the stimuli; word frequency-dependent differences in word recognition have been attributed to differences in the ease of lexical access (Diependaele et al., 2013; Grainger, 1990). The idea is that more frequent words provide more top-down feedback from the lexical level that facilitates word recognition. Effects of cross-level ortho-lexical interactions then contrast with effects resulting from within-level lexical-lexical interactions that produce competition. Thus, frequency effects should persist in noise as long as the stimuli are still intelligible (performance not at floor) (de Zuniga et al., 1991; de Zuñiga et al., 1991; and Perea et al., 2016; Roldán et al., 2018). Increased frequency effects, for more visually ambiguous stimuli have also been observed, and have been attributed to increased reliance on top-down processes, see Besner and Young (2022) for discussion. On the one hand, noise may increase lexical competition (including crosslinguistic competition), and on the other hand, noise may increase reliance on top-down effects of frequency. Thus, we predict an interactive effect of frequency and noise that depends on the cognate status of the word.

2. Methods

Participants. Thirty-five Spanish-English bilinguals (22 female) took part in this first experiment (see Supplementary Materials, Appendix A for participant profile). One participant was removed as an outlier. Participants’ language proficiency was assessed using a picture naming task (BEST task) (for further details see de Bruin et al. (2017), requiring a score of >40 on the English BEST test (equivalent to an English intermediate level). None of the participants reported any history of reading, hearing, speech or psychiatric disorders. All participants signed an informed consent before they performed the experiment. The experiment was conducted in accordance with the Declaration of Helsinki and approved by the Basque Center on Cognition, Brain and Language ethics committee. Participants were paid for their participation.

Stimuli. The stimulus set consisted of 264 words and 264 pseudowords. The words were divided into four categories: high and low frequency cognates and non-cognates (see Supplementary materials, Appendix B for additional details). Words were matched across conditions on the following characteristics: number of letters, phonemes, phonological and orthographic neighbors (based on CLEARPOND database (Marian et al., 2012)), number of syllables, and concreteness (based on MRC Psycholinguistics database; Coltheart, 1981), age of acquisition (AoA, based on Schock ratings; Schock et al., 2012). Word frequency calculations were based on CLEARPOND (low word frequency = 0.12-14.29, high word frequency = 14.43-419.29), orthographic cognate rate (Levenshtein distance formula (corrected for length; Yujian & Bo, 2007), cognates ≥ 0.50). Pseudowords were created using the Wuggy software program (Keuleers & Brysbaert, 2010), and all of them were matched with words on length and number of orthographic neighbors. Visual noise was generated using PsychoPy (Peirce, 2007).[1]

Procedure. Participants were tested individually in a quiet room. They were seated at a distance of approximately 60 cm from a computer screen, and stimuli were presented in black 38-point uppercase letters in Arial font on a dark grey background. The experiment was programmed and presented using version 1.83.04 of PsychoPy (Peirce, 2007).

Each trial began with the presentation of a fixation cross (‘+’) appearing in the center of the screen for 500 ms. The target stimulus appeared after 500 ms and remained on the screen until the participant responded or until 1500 ms after stimulus onset. Participants were instructed to press one button if they thought the letter string was an English word, and a different button if it was not, as quickly and accurately as possible. Following the response, a blank grey screen appeared for 500 ms before the next trial. The experiment had four self-paced breaks. Prior to the experiment, participants performed a practice block (4 trials).

Two separate sessions occurred on different days at least two weeks apart: one blocked and one intermixed, counterbalanced across participants. There were 66 items per condition: Half of the items were presented in clear and the other half were embedded in noise. Clear and noisy targets were counterbalanced across participants so that none of the participants were presented with the same word

[1] A 512x512-pixel matrix was filled with random dots positioned over the stimuli covering 81% of the visual word with signal-correlated noise. Examples of these are provided in the supplementary materials.

across conditions, in either session. In the 'blocked' presentation, target words were presented in two homogeneous blocks, one containing only clear stimuli and the other one containing noisy stimuli, counterbalanced across participants. In the 'intermixed' presentation, the different clear and noisy targets were intermixed, presented in a different random order for each participant.

3. Results

Analysis. The reaction time (RT) analysis was conducted on correct responses to words. RTs that were 2.5 standard deviations above or below the mean for a given participant (2.06% of all trials) were removed. Mixed linear models were performed on accuracy and reactions time measures. We used a forward-stepping approach, starting from a simple model including the factor Cognate Status, by-item and by-subject random intercepts. The other experimental factors (Intelligibility, Word frequency, Presentation Sequence) and relative interactions were incrementally added in subsequent steps. Random slopes were not included because none of the tested models converged after adding these random factors. Nested model comparisons were carried out to define the best fitting model. All statistical analyses were performed using R 4.0.0 (R core team, 2021). Follow-up tests were performed with the emmeans package (Searle et al., 1980) and corrected for multiple comparisons using multivariate t distributions (mvtnomr package, https://cran.r-project.org/web/packages/mvtnorm/index.html).

Results. *Accuracy.* Table 1 provides accuracy results for each of the experimental conditions. The best fitting model included Cognate Status, Word frequency, Intelligibility, their interactions, and the random intercepts (c2 = 45.13, p = 10e-7, R2 = 0.44). There was a main effect of Intelligibility (b = −1.23, SE = 0.03, t = 41.97, p = 10e-16) and Word frequency (b = −0.56, SE = 0.05, t = 12.01, p = 10e-16). Responses were more accurate for clear than noisy words. Accuracy was higher with high than low word frequency words. The interactions Word frequency x Intelligibility (b = 0.28, SE = 0.03, t = 10.01, p = 10e-16) and Word frequency x Cognate Status (b = −0.15, SE = 0.05, t = 3.15, p = 0.002) were significant, suggesting that the cognate effect was present only in low word frequency items (low frequency: b = −0.42, SE = 0.12, t = 3.52, p = 0.0018; high frequency: b = 0.17, SE = 0.14, t = 1.17, p = 0.5838). The three-way interaction Word frequency x Intelligibility x Cognate Status was also significant (b = 0.08, SE = 0.03, t = 2.81, p = 0.005) (see Fig. 1). The word frequency effect (i.e., higher accuracy for high than low frequency words) was significant in both clear and noisy signal (clear: b = −1.68, SE = 0.13, t = 13.24, p = 0.0001, noise: b = −0.55, SE = 0.09, t = 6.31, p = 0.0001). Post-hoc tests for the three way interaction Word frequency x Intelligibility x Cognate Status showed a difference in the magnitude of the cognate effect with low word frequency words yielding a strong cognate effect in clear but not noise (low word frequency, clear: b = −0.65, SE = 0.14, t = 4.61, p = 0.001; low word frequency, noise: b = −0.19, SE = 0.12, t = 1.52, p = 0.69; high word frequency comparisons: ts $<$ 1.3, ps $>$ 0.80). Adding the factor Presentation Sequence (block vs intermixed) did not improve the model fit (c2 = 10.79, p = 0.21).

Reaction Time. Table 2 provides reaction times for each condition. The best fitting model included Cognate Status, Word frequency, Intelligibility, Presentation Sequence, their interactions, and the random intercepts (c2 = 198.16, p = 10e-16, R2 = 0.56). There were main effects of Intelligibility (b = 173.95, SE = 1.56, t = 111.26, p = 10e-16), Cognate Status (b = 10.38, SE = 3.29, t = 3.15, p = 0.002), Word frequency (b = 33.0, SE = 3.29, t = 10.03, p = 10e-16), and Presentation Sequence (b = 9.84, SE = 1.56, t = 6.33, p = 10e-10). Responses were faster for clear signal than noisy signal. Cognates had faster responses than non-cognates. High word frequency words showed faster responses than low word frequency words. Finally, the blocked design showed faster responses than the intermixed design. In addition, the interaction Cognate Status x Intelligibility was also marginally significant here (b = −3.01, SE = 1.56, t = 1.93, p = 0.05). The cognate effect was present for clear but not noisy words (clear: b = 26.8, SE = 6.96, t = 3.85, p = 0.0005; noise: b = 14.7, SE = 7.59, t = 1.94, p = 0.17). The interaction Cognate Status x Word frequency was significant (b = 11.34, SE = 3.29, t = 3.45, p = 0.0007). The cognate effect was present only for low word frequency items (low frequency: b = 43.43, SE = 9.43, t = 4.61, $p < 0.0001$; high frequency: b = −1.92, SE = 9.19, t = 0.21, p = 0.9957). The word frequency effect was significant across all conditions (cognates: b = 43.33, SE = 9.28, t = 4.67, p = 0.0001; non-cognates: b = 88.69, SE = 9.34, t = 9.50, p = 0.0001). None of the other interactions reached significance (ts $<$ 1.4, ps $>$ 0.15).

4. Discussion

The results of this experiment showed that intelligibility had an influence on cognate facilitation effects. When L2 stimuli were presented in the clear, lexical decisions for cognates were faster than for non-cognates, replicating the well-established cognate facilitation effect (De Groot & Nas, 1991). However, when stimuli were embedded in visual noise, there was no difference in lexical decision reaction times between cognates and non-cognates, and no difference in accuracy measures. Thus, noise essentially reduced the benefit of cognate status. As expected, the frequency effect persisted in noise, suggesting that differences in L2 lexical access could still be detected in this task. Note that, in the current experiment, the cognate facilitation effect only emerged in the clear condition. Furthermore, the accuracy results show that the cognate effect, in the clear, was mainly driven by low frequency words, a finding that has previously been observed (Peeters et al., 2013). Perhaps the threshold of lexical activation affects the degree to which cognate status provides a benefit, and cognate effects could depend on many factors that affect lexical access including individual differences in a lexical item, the task condition, or participant characteristics.

Motivated by BIA+'s separate task-level system that does *not* have top-down effects on word-level processes or language-selective inhibition (Dijkstra & Van Heuven, 2002), we also manipulated the presentation sequence of noisy and clear stimuli (in Experiment 1) due to its known differential impact on local compared to global task-level processes. The fact that there was no significant two-way

Table 1
Mean proportion of correct lexical decisions on word targets from each condition. Standard deviations are in Parentheses.

	Blocked				Intermixed			
	Clear		Noise		Clear		Noise	
	Cog	NonCog	Cog	NonCog	Cog	NonCog	Cog	NonCog
High Frequency	0.97 (0.04)	0.97 (0.03)	0.68 (0.15)	0.68 (0.20)	0.97 (0.03)	0.98 (0.03)	0.64 (0.17)	0.67 (0.16)
Low Frequency	0.89 (0.06)	0.82 (0.12)	0.57 (0.17)	0.52 (0.16)	0.91 (0.07)	0.84 (0.09)	0.56 (0.19)	0.53 (0.16)

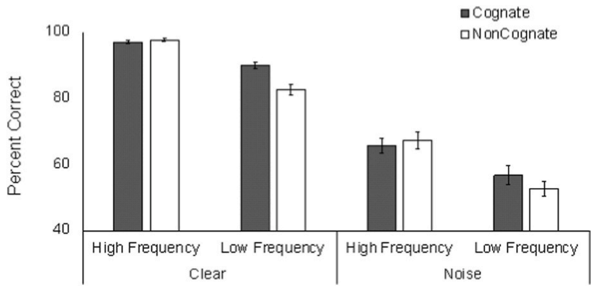

Fig. 1. Percent correct on lexical decisions for words reflecting 3-way interaction between Cognate Status, Intelligibility, and Word Frequency.

Table 2
Mean reaction times for correct responses measured from onset of stimulus for each condition. Standard deviations are in Parentheses.

	Blocked				Intermixed			
	Clear		Noise		Clear		Noise	
	Cog	NonCog	Cog	NonCog	Cog	NonCog	Cog	NonCog
High Frequency	619 (85)	623 (85)	971 (150)	964 (144)	633 (70)	636 (74)	1002 (122)	986 (117)
Low Frequency	654 (102)	704 (114)	1018 (142)	1049 (152)	676 (76)	723 (92)	1045 (145)	1073 (123)

interaction between cognate status and presentation sequence or three-way interaction between cognate status, intelligibility, and presentation sequence suggests that presentation sequence did not impact the effect of noise on crosslinguistic interactions. Thus, general task-level effects of noise on overall performance do not seem to influence the effects of noise on the local processes involved in the crosslinguistic lexical interactions.[2]

Based on interactive models of bilingual lexical processing, we predicted that the reduced cognate effect in noise should relate to increased crosslinguistic interactions. The aim of Experiment 2 is to further probe the modulatory effect of stimulus intelligibility on cognate effects. Based on prior studies in the auditory, Experiment 2 investigates the potential for differences in crosslinguistic lexical competition that result from the cognate status and intelligibility of the visual input.

5. Experiment 2

To more directly test whether stimulus intelligibility effects on cognate facilitation are due to relatively greater effects of cross-linguistic competition, Experiment 2 manipulates the number of orthographic neighbors for the target's translation equivalents ($OrthND_{trans}$) employing a visual intelligibility manipulation that is more ecological than that used in Experiment 1, namely, font difficulty.

The number of inter-language (within) *and* intra-language (crosslinguistic) neighborhood influences bilingual word recognition (Dirix et al., 2017; Van Heuven et al., 1998). For example, Dijkstra and Van Heuven (1998) showed that Dutch-English (L1-L2) bilinguals perform worse on English words that have a larger Dutch phonological neighborhood. In addition, interactive models of L2 lexical processing predict co-activation of the L1 translation ($OrthND_{trans}$) to be greater for cognates, and should consequently co-activate the translation's neighborhood. Because the cognate L2 neighborhoods have greater orthographic overlap with L2 targets, these are predicted to induce increased lexical competition relative to noncognates.

We directly test for this prediction by manipulating the number of neighbors for the L1 translation equivalents (keeping constant

[2] In the original BIA model (preceding BIA+), the word identification system consists of language nodes which can selectively inhibit lexical items in the unattended language, thereby acting as language filters (Dijkstra et al., 1998). BIA did not incorporate effects of non-linguistic factors so it is not clear whether the language nodes could be modulated by noise to selectively suppress on language, in that model.

the number of L2 neighbors across conditions); for example, the English word ‘route’ is ‘ruta’ in Spanish and includes its neighbors ‘rata’, ‘rota’, etc., We predicted an interaction between cognate status and this measure of neighborhood density whereby L2 targets with a greater number of L1 translation neighbors ($OrthND_{trans}$) impair lexical decisions for cognates more than for non-cognates due to the relative orthographic similarity across languages. In addition, we expected crosslinguistic competition effects, from neighbors in the non-target language, to be greater for less intelligible stimuli.

In addition to the manipulation of orthographic neighborhood density, we included a word frequency manipulation, as we did in Experiment 1. However, the creation of a balanced intelligibility × $OrthND_{trans}$ × cognate status × word frequency experimental design was not possible. So, stimulus factors were manipulated such that two sets of analyses could be conducted separately to examine interactions between intelligibility and cognate status, with 1) word frequency, and 2) neighborhood density. Thus, any cognate × frequency interactions found for the frequency design would not be explained by lexical competition between L1 neighbors, any interactions between cognate status and neighborhood density would not be explain by top-down effects of frequency for the neighborhood density design.

6. Methods

Participants. Forty Spanish-English bilinguals (33 female) took part in Experiment 2 (see Supplementary Materials, Appendix A for additional information about participant profile). As in Experiment 1, participants' language proficiency was assessed using the BEST test (de Bruin et al., 2017) requiring a score >40. Participants had no history of reading, hearing, speech or psychiatric disorders. The experiment was approved by the institution's ethics committee, in accordance with the Declaration of Helsinki. All participants, in the main experiment, signed an informed consent before they performed the experiment and were paid for their participation.

Stimuli. 344 words and 344 pseudowords were selected for the experiment across both designs -all of which were included in the Neighborhood design; half were words with L1 translations that had a low neighborhood density (0-1) and the other half had a high neighborhood density (3-29)] controlling for number of L2 neighbors across conditions (see Supplementary materials, Appendix D for additional details). A subset of these (296 words) were used for the Word frequency design; half were low word frequency words, and the other half were high word frequency words, controlling for L1 word frequency. Word frequency measures were based on CLEARPOND database (Marian et al., 2012; ranges: low word frequency words = 0.45-17.27, high word frequency words = 17.88-439). As in Experiment 1, additional lexical characteristics were matched across conditions. For more stimulus details, see Supplementary Materials. Items were divided into intelligibility conditions (easy font, difficult font), counterbalanced across participants (see Supplementary materials, Appendix C for additional stimulus details). The creation of the pseudowords also followed the procedure from experiment 1 and all were matched with words on length and number of orthographic neighbors (all $ps > 0.30$). Pilot work determined the font used for the experiment.

The piloting phase of this experiment, which aimed to select the easy and difficult-to-read fonts for the stimulus intelligibility manipulations, was conducted with 24 unpaid student-friend volunteers (12 females; mean age = 30.8; SD = 4.9). Participants rated the level of difficulty and familiarity, on a scale of 1-10, for 61 different fonts. One ‘easy-to-read’ font and one ‘difficult-to-read’ font was selected based on participants' ratings: 41.5-point ‘Sanies Script’ for the easy condition, and 38-point ‘Rangga Script’ for the difficult condition (examples of these are provided in the Supplementary Materials). These showed a significant difference in difficulty but not familiarity ratings. The difficulty rating (mean ‘easy-to-read’ = 3.5; SD = 2.4; mean ‘difficult-to-read’ = 5.9; SD = 2.7) differed significantly between conditions ($p < 0.001$). The familiarity rating (mean ‘easy-to-read’ = 4.5; SD = 2.2; mean ‘difficult-to-read’ = 3.4; SD = 2.4), however, did not differ significantly (p = 0.13). The font size ensured that the easy and difficult conditions occupied the same space on the screen.

Procedure. The trial procedure followed that from Experiment 1 beginning with the presentation of a fixation cross (‘+’), target stimulus presentation, and response. The experiment had four self-paced breaks. The total task duration was approximately 20 min.

Analysis. The reaction time analysis was conducted on correct responses to words. Reaction times that were 2.5 standard deviations above or below the mean for a given participant were removed (4.37% of all trials). As in Experment 1, mixed linear models were performed. We started from a simple model including the factor Cognate Status, by-item and by-subject random intercepts. The other experimental factors (1) Neighborhood Design: Intelligibility (difficult font, easy font), Neighborhood density (high, low); 2) Word Frequency Design: Intelligibility, Word frequency) and relative interactions were incrementally added in subsequent steps. Random slopes were not included because none of the models tested converged after adding these random factors. Nested model comparisons were carried out to define the best fitting model.

Table 3
Mean proportion of correct lexical decisions on word targets from each condition in the Frequency Design. Standard deviations are in Parentheses.

Easy font				Difficult font			
High frequency		Low frequency		High frequency		Low frequency	
Cog	NonCog	Cog	NonCog	Cog	NonCog	Cog	NonCog
0.95 (0.05)	0.93 (0.05)	0.81 (0.10)	0.72 (0.10)	0.89 (0.07)	0.86 (0.08)	0.71 (0.13)	0.66 (0.12)

7. Results

7.1. Word frequency design

Accuracy. Table 3 provides accuracy scores. The model including Cognate Status and Intelligibility provided the best fit of the data (c2 = 128.91, p = 10e-16, R2 = 0.44). Main effects of Cognate Status (b = −0.22, SE = 0.09, t = 2.42, p = 0.02) and Intelligibility (b = −0.32, SE = 0.03, t = 11.42, p = 10e-16) were found. Accuracy was higher for easy compared to difficult font and for cognates compared to non-cognates. The Cognate Status × Intelligibility interaction was also significant (b = 0.06, SE = 0.03, t = 2.00, p = 0.04) (see Fig. 2). A significant cognate effect was observed for the easy font (b = −0.56, SE = 0.19, t = 2.86, p = 0.02), but not for the difficult font (b = −0.33, SE = 0.19, t = 1.76, p = 0.24). This replicates the findings in Experiment 1, confirming a reduction in the cognate facilitation effect for the less intelligible stimulus condition.

Yet again, the model including the factors Cognate Status and Word frequency was a better fit than the starting model (c2 = 86.72, p = 10e-16, R2 = 0.42). There was a main effect of Cognate Status (b = −0.21, SE = 0.08, t = 2.65, p = 0.008) and Word frequency (b = −0.78, SE = 0.08, t = 9.99, p = 10e-16), but no interaction (b = −0.02, SE = 0.08, t = 0.20, p = 0.84). Responses were more accurate for cognates than non-cognates, and for high word frequency than low word frequency words.

Reaction Time. Table 4 provides the reaction times. The best fitting model included Cognate Status, Intelligibility, Word frequency, their interactions, and the random intercepts (c2 = 98.81, p = 10e-16, R2 = 0.37). A main effect of Cognate Status was observed (b = 14.16, SE = 3.91, t = 3.63, p = 0.0003), with faster responses for cognates compared to non-cognates. A main effect of Intelligibility (b = 52.28, SE = 1.64, t = 31.97, p = 10e-16) was also present, with faster responses for the easy compared to the difficult font. There was a main effect of Word frequency (b = 39.33, SE = 3.91, t = 10.07, p = 10e-16), with faster responses for high than low word frequency words. Again, Cognate Effects were modulated by intelligibility; the interaction Cognate Status x Intelligibility x Word frequency was significant (b = 3.45, SE = 1.63, t = 2.11, p = 0.03). Follow-up t-tests showed that there was a significant word frequency effect in all conditions (easy font, cognates: b = 90.3, SE = 11.81, t = 7.64, p = 0.0001; easy font, non-cognates: b = 76.7, SE = 11.96, t = 6.41, p = 0.0001; hard font, cognates: b = 66.8, SE = 12.0, t = 5.57, p = 0.0001; hard font, non-cognates: b = 80.9, SE = 12.13, t = 6.67, p = 0.0001); in this case, the cognate effect was present only in high word frequency items presented in the easy font (high frequency, easy font: b = 39.8, SE = 11.62, t = 3.43, p = 0.0075; high frequency, difficult font: b = 16.5, SE = 11.76, t = 1.41, p = 0.7643; low frequency, easy font: b = 26.3, SE = 12.14, t = 2.17, p = 0.2550; low frequency, difficult font: b = 30.6, SE = 12.36, t = 2.48, p = 0.1264). However, we note that the stimulus intelligibility manipulation in this experiment was less challenging compared to Experiment 1 (faster reaction times). In addition, the easy font manipulation was still more difficult than the clear condition in Experiment 1. Taken together, these two factors potentially contribute to cognate effects emerging in high frequency items as easy font may still require top-down processing (Vergara-Martínez et al., 2021).

7.2. Neighborhood Design

Accuracy. Table 5 provides the accuracy scores. The model including the factors Cognate Status and Neighborhood density reached a better fit than the starting model (c^2 = 7.22, p = 0.03, R2 = 0.43). There was a main effect of Neighborhood density (b = 0.19, SE = 0.08, t = 2.31, p = 0.02) but no interaction between Neighborhood density and Cognate Status (b = −0.12, SE = 0.08, t = 1.47, p = 0.14). Responses were more accurate for words with lower compared to higher Neighborhood densities. Adding the factors of Cognate Status, Intelligibility, Neighborhood density, and their interactions did not improve the model fit compared to the previous simpler models (c2 = 0.00, p = 0.99).

The model including Cognate Status and Intelligibility also provided a better fit of the data compared to the starting model (c2 = 137.15, p = 10e-16, R2 = 0.44). Main effects of Cognate Status (b = −0.23, SE = 0.08, t = 2.7, p = 0.007) and Intelligibility (b = −0.31, SE = 0.03, t = 11.82, p = 10e-16) were observed. Cognates were associated with better performances than non-cognates. Similarly, the easy font showed more accurate responses than the difficult font. However, the interaction between these two factors (b = 0.04, SE = 0.03, t = 1.48, p = 0.14) did not reach significance, in this model.

Reaction Time. Table 6 provides reaction times. The best fitting model included Cognate Status, Intelligibility, Neighborhood density, their interactions, and the random intercepts (c2 = 15.75, p = 0.003, R2 = 0.38). A main effect of Cognate Status was observed (b = 14.49, SE = 4.23, t = 33.94, p = 10e-16), with faster responses for cognates compared to non-cognates. A main effect of Intelligibility (b = 51.58, SE = 1.52, t = 2.7, p = 0.007) was also present, with faster responses for the easy compared to the difficult font. The interaction between Cognate Status and Neighborhood density was significant (b = 8.75, SE = 4.23, t = 2.07, p = 0.04): faster responses for cognates compared to non-cognates was only observed for words with a low neighborhood density (low: b = 46.47, SE = 11.9, t = 3.90, p = 0.0005; high: b = 11.47, SE = 12.0, t = 0.95, p = 0.73). This asymmetry was due to a reduction of response times for words with a low compared to a high number of Neighborhood density, which was specific to cognate words (cognate: b = −30.93, SE = 11.9, t = 2.59, p = 0.04; noncognate: b = −4.07, SE = 12.0, t = 0.34, p = 0.98) (see Fig. 3). The Intelligibility x Neighborhood density was also significant (b = −4.42, SE = 1.53, t = 2.90, p = 0.004), showing a marginal effect of Neighborhood density (i.e. faster responses for words with a low neighborhood density) for the difficult font condition but not for the easy font condition (difficult: b = −22.28, SE = 9.05, t = 2.46, p = 0.05; easy: b = −4.59, SE = 8.95, t = 0.51, p = 0.95). Interactions between Cognate Status and Intelligibility did not reach significance (ts < 1, ps > 0.40) (see Fig. 4).

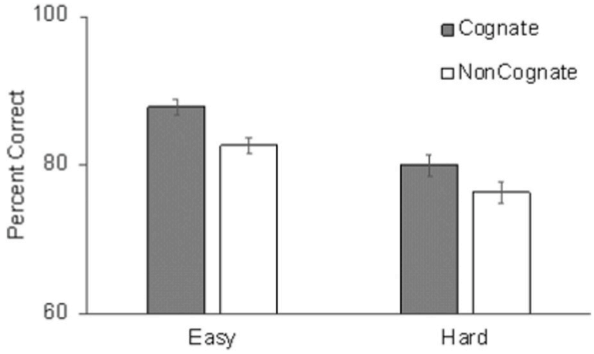

Fig. 2. Cognate × Intelligibility Interaction. Y-axis shows Percent accuracy. Error bars represent standard error of the means.

Table 4
Mean reaction times for correct responses measured from onset of stimulus for each condition in the Frequency design. Standard deviations are in Parentheses.

Easy font				Difficult font			
High frequency		Low frequency		High frequency		Low frequency	
Cog	NonCog	Cog	NonCog	Cog	NonCog	Cog	NonCog
703 (68)	742 (73)	782 (81)	808 (89)	822 (86)	838 (72)	884 (108)	910 (99)

Table 5
Mean proportion of correct lexical decisions on word targets from each condition in the Neighborhood Design. Standard deviations are in Parentheses.

Easy font				Difficult font			
High OrthNDtrans		Low OrthNDtrans		High OrthNDtrans		Low OrthNDtrans	
Cog	NonCog	Cog	NonCog	Cog	NonCog	Cog	NonCog
0.86 (0.11)	0.82 (0.11)	0.90 (0.07)	0.83 (0.10)	0.76 (0.13)	0.73 (0.14)	0.85 (0.08)	0.79 (0.12)

8. Discussion

Without taking into consideration the neighborhood density of the translation equivalents, the results of Experiment 2 again show the expected overall facilitatory effect of cognate status on visual word recognition. As in Experiment 1, this facilitation was again reduced for the less intelligible condition, this this case the more difficult to read font. The result was consistent across accuracy and reaction time analyses, thereby extending the finding of Experiment 1 (with noise) to a different manipulation of intelligibility. As expected, both experiment 1 and 2 show significant frequency effects across all conditions.[3]

Turning to the neighborhood analysis, as expected, both intelligibility and high $OrthND_{trans}$ density had a negative effect on visual word recognition performance. Lexical decision accuracy was lower, and reaction times were slower for less intelligible stimuli. These were also slower and less accurate for stimuli with a high number of orthographic neighbors. These findings are consistent with the notion that co-activated lexical candidates from the L1 translation compete for selection during lexical decision task in the L2.

In addition, adding $OrthND_{trans}$ as an interacting factor with Cognate Status provided a better fit of the data than models that did not, consistent with our hypothesis that translations with high orthographic neighborhood densities led to a more detrimental effect on visual word recognition for cognates compared to non-cognates. Significant cognate facilitation effects were only for words with few orthographic neighbors, suggesting that increased cross-linguistic competition for cognates may offset the overall benefits of cognate status on bilingual visual word recognition. One interpretation of this result is that the benefit of feedback from shared semantic activation depends on the extent of inhibitory lateral interactions at the lexical level. As orthographic neighborhood density increases, lexical competition may outweigh any top-down semantic facilitation.

Importantly, because cognate facilitation effects are often taken as evidence for language co-activation, a reduction of cognate facilitation could at first glance be interpreted as a reduction in the activation of the unattended language (in this case L1). However, the current experiment shows that cognates are more susceptible to crosslinguistic competition. Intelligibility does not seem to

[3] However, unlike Experiment 1, the interaction effect between cognate status and intelligibility on word recognition accuracy was not significantly modulated by word frequency here; across experiments, stimulus list composition, overall performance, and participants differed, potentially contributing to the observed cognate effects on higher word frequency items (not observed in Experiment1).

Table 6
Mean reaction times for correct responses measured from onset of stimulus for each condition in the Neighborhood design. Standard deviations are in Parentheses.

Easy font				Difficult font			
High OrthNDtrans		Low OrthNDtrans		High OrthNDtrans		Low OrthNDtrans	
Cog	NonCog	Cog	NonCog	Cog	NonCog	Cog	NonCog
756 (85)	765 (71)	740 (81)	781 (84)	871 (100)	876 (86)	827 (87)	878 (88)

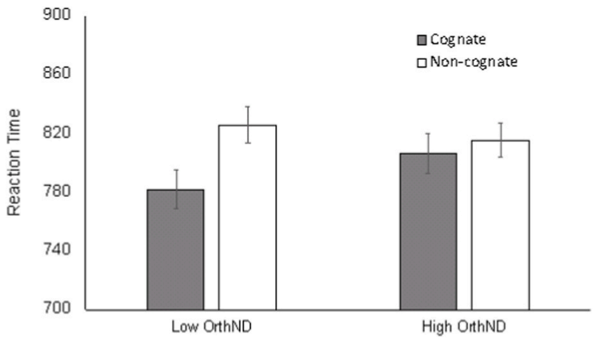

Fig. 3. Reaction Times for accurate responses showing an interaction between Cognate Status and Neighborhood Density.

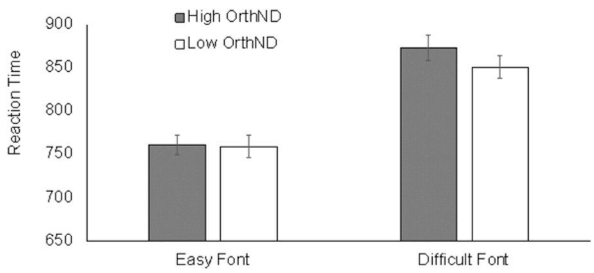

Fig. 4. Reaction Times for accurate responses showing an interaction between Intelligibility and Neighborhood Density.

attenuate the activation of L1, and any observed reduction in cognate facilitation is more likely to be due to other factors that depend on crosslinguistic interactions, such as crosslinguistic competition. What is clear is that despite the influence of other lexical factors on L2 word recognition, L1 influences on L2 word recognition persist under challenging (less intelligible) conditions consistent with interactive non-selective models of bilingual lexical access.

9. General discussion

Readers often encounter text that varies in visual quality. For example, nonstandard fonts and other types of text degradations can be difficult to read and can negatively impact visual word recognition. For bilinguals, such reductions in visual intelligibility can impact lexical activation across two languages. Yet, until now, the effect of intelligibility on visual word recognition, as a function of crosslinguistic interactions in bilinguals has not been examined. The goal of the current study was to explore the impact of stimulus intelligibility on crosslinguistic effects. Two experiments investigated whether the well-established cognate facilitation effect was modulated by different challenging visual stimulus manipulations, namely visual noise (Experiment 1) and a difficult font (Experiment 2).

Across both experiments, the expected detrimental effect of intelligibility on visual word recognition was found. A main effect of cognate status was also found showing an overall benefit for cognates (faster and more accurate recognition), and replicating the classic cognate facilitation effect found in prior studies. However, cognate effects were not facilitatory in all conditions. Rather, the data suggest that cognate status results in the activation of two competing effects on word recognition. On the one hand, facilitation occurs due to feedback from shared crosslinguistic semantics onto the lexical level. On the other hand, enhanced crosslinguistic interactions activate additional potential candidates, which compete with one another. In the presence of high crosslinguistic competition, cognate facilitation fades.

Across both experiments, we showed an interaction between intelligibility and cognate status. In fact, lexical decisions were relatively slower and less accurate for cognates in noise (Experiment 1) or in a difficult font (Experiment 2). Experiment 2 explored one potential mechanism for this reduction by directly testing crosslinguistic interaction effects that arise from lexical-semantic-lexical interactions. In Experiment 2, cognates were more susceptible to effects of neighborhood density associated with cognate L1 translations. Because L2 neighbors are more orthographically similar in form to the L2 target than non-cognate neighbors, this likely leads to increased crosslinguistic lexical-lexical competition.

Overall, the findings are consistent with an architecture that allows effects of visual manipulations to propagate up the lexical hierarchy (bottom-up), within and across languages blurring the distinction between similar lexical forms (cognates). In the context of models that allow for top-down semantic feedback, L2-L1 lexical competition effects could be mitigated by overlapping crosslinguistic top-down semantic-orthographic interactions, for cognates. This could explain why we did not find an increase in neighborhood effects for cognates presented in a difficult font. Together with the results of Experiment 1, the results of Experiment 2 suggest that cognate facilitation effects are not a given, despite L2-L1 lexical co-activation. The results speak to several aspects of bilingual research. Below, we briefly discuss some of the implications.

Methodological implications. Our results add to a growing literature on the multiple factors that can impact L2 lexical processing. Specifically, we point to effects of stimulus intelligibility and cognate status that depend on neighborhood density effects. We emphasize that the absence of cognate effects does not necessarily imply language-selective activation. Rather, factors such as crosslinguistic competition that increase under low intelligibility conditions likely impact performance and dampen cognate effects. This interpretation is consistent with the functional architecture of models that propose automatic bottom-up language-coactivation. However, addressing the modulatory effects of stimulus quality and other factors is critical to the evolution of more detailed models that aim to account for human behavior, in the natural world.

Implications of models of bilingual lexical processing. Overall, the findings reaffirm a growing consensus that the unattended L1 is automatically co-activated, regardless of whether cognate facilitation can be observed. Although bilingual models of visual word recognition have not explicitly accounted for potential effects of stimulus quality, our findings are consistent with an interactive architecture that would predict an effect of intelligibility on bottom-up processes that contribute to within and crosslinguistic lexical competition. The results of Experiment 2 that show a persistent effect of $OrthND_{trans}$ suggest that intelligibility does not reduce crosslinguistic lexical interactions, consistent with non-selective language activation. Together, the findings are important for moving towards a more brain-based model of bilingualism providing new insight into how bilingual word recognition is shaped by perceptual encoding, lexical competition, and overlapping semantic/conceptual representations and their interactions. Indeed, the success of recent computationally-based neural models that better predict behavior under challenging visual settings depends on feedback and recurrent networks (Wyatte et al., 2012). Interactive models like BIA+ (Dijkstra & van Heuven, 2002), with a local influence of L1 on L2 lexical processing, can be extended to incorporate earlier sensory processes and mapped onto brain regions. Future experiments should consider the inclusion of multiple concurrent manipulations to disentangle among competing interpretations of the same crosslinguistic behavioral effect.

Practical implications. A second language learner's experience of reading in classrooms and in more naturalistic social settings, often involves visual input that is more difficult to decipher than the standard text found in books. These findings suggest that intelligibility affects crosslinguistic interactions that may consequently impact L2 comprehension, and in turn learning. Studies have shown that semantic context can mitigate the negative effects of noise on crosslinguistic competition (Becker, 1979; Clark et al., 2021;Guediche et al., 2020; Guediche et al., 2021; Perea et al., 2008). Thus, pedagogical practices may benefit from incorporating contextual factors to reduce crosslinguistic competition and facilitate semantic access.

CRediT authorship contribution statement

Sara Guediche: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Eugenia Navarra-Barindelli:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Sendy Caffarra:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Clara Martin:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Disclosure statement

The authors have no competing interests.

Declaration of competing interest

The authors declare they have no financial conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jneuroling.2026.101339.

Data availability

Publicly available data https://osf.io/s584m/?view_only=ac42ceba035b43bab17032297e035c20.

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