Covert co-activation of bilinguals' non-target language

Phonological competition from translations

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When listening to spoken language, bilinguals access words in both of their languages at the same time; this co-activation is often driven by phonological input mapping to candidates in multiple languages during online comprehension. Here, we examined whether cross-linguistic activation could occur *covertly* when the input does not overtly cue words in the non-target language. When asked in English to click an image of a duck, English-Spanish bilinguals looked more to an image of a shovel than to unrelated distractors, because the Spanish translations of the words duck and shovel (*pato* and *pala*, respectively) overlap phonologically in the non-target language. Our results suggest that bilinguals access their unused language, even in the absence of phonologically overlapping input. We conclude that during bilingual speech comprehension, words presented in a single language activate translation equivalents, with further spreading activation to unheard phonological competitors. These findings support highly interactive theories of language processing.

Keywords: language comprehension, language co-activation, bilingualism

1. Introduction

The present research focuses on the consequences of bilingualism for spoken language processing. We aim to study how experience, particularly experience with two languages, configures cognitive and linguistic architectures. An emerging body of research on bilingualism points to a remarkable discovery – that bilinguals' two languages are co-activated in parallel. Research exploring language co-activation in bilinguals indicates that a bilingual's two languages can interact at various levels of processing. For instance, cross-linguistic priming effects have been found at both lexical (Finkbeiner, Forster, Nicol, & Nakamura, 2004; Schoonbaert, Duyck,

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Brysbaert, & Hartsuiker, 2009) and syntactic (Hartsuiker, Pickering, & Veltkamp, 2004; Loebell & Bock, 2003) levels, and there appears to be a close relationship between orthography and phonology across languages in bilinguals (Kaushanskaya & Marian, 2007; Thierry & Wu, 2007). Furthermore, bilinguals have been shown to co-activate lexical items in their two languages across highly diverse language pairs (Blumenfeld & Marian, 2007; Canseco-Gonzalez et al., 2010; Cutler, Weber, and Otake, 2006; Thierry & Wu, 2007; Weber & Cutler, 2004). Some of the most compelling evidence for language co-activation comes from eye-tracking studies, which often rely on phonological overlap between cross-language word pairs (e.g., English "marker" and Russian "marka"/*stamp*; Marian & Spivey, 2003a). Importantly, cross-linguistic effects appear sensitive to fine-grained acoustic details, such as voice-onset time (e.g., Ju & Luce, 2004), or degree of phonological overlap (e.g., Marian, Blumenfeld, and Boukrina, 2008), suggesting that linguistic co-activation may be primarily driven by phonological or auditory features. One of the principal forces behind the phonologically-mediated studies of language co-activation is ambiguity in the incoming auditory information. In other words, the *overt* presentation of ambiguous information in the signal causes the language system to entertain all candidates, independent of language, that could potentially match the input.

Alternatively, recent research has explored the possibility that cross-language activation during comprehension may not require *overt* input in a target language in order to activate a non-target language. Thierry and Wu (2007) performed an ERP study examining Mandarin-English bilinguals' responses to English words that were not phonologically related in English (e.g., *novel* and *violin*), but overlapped in both orthography and phonology in Mandarin. When asked to judge the semantic relationship between pairs of English words whose translations shared Chinese orthography and phonology, bilinguals showed a reduction of the N400, which has been shown to underlie semantic processing (Kutas & Federmeier, 2000; Lau, Phillips, & Poeppel, 2008). In a follow-up study, Wu and Thierry (2010a) used the same semantic judgement task, with a set of English words whose Chinese translations had either repeated phonology, repeated orthography, or neither. The authors found that translation pairs that shared phonology modulated the N400 effect, whereas pairs that repeated orthography did not, indicating that across both studies, the phonology of the unpresented translations drove access to the non – target language in Chinese-English bilinguals. Likewise, Zhang, van Heuven, and Conklin (2011) found that Chinese-English bilinguals responded more quickly to English prime-target word pairs whose Chinese translations shared the first morpheme than to English word pairs with no overlap in Chinese translation, even when the prime was presented for only 59 ms and masked.

Studies of bimodal bilinguals (users of a spoken and a signed language) have corroborated the implicit activation account (Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Van Hell, Ormel, van der Loop, & Hermans, 2009). For example, Morford et al. (2011) performed a study where deaf American Sign Language-English bilingual participants judged printed word pairs as semantically related (BIRD/DUCK) or semantically unrelated (MOVIE/PAPER). Some of the contrasts consisted of words whose translation equivalents overlapped in ASL phonology. When the translations overlapped in ASL phonology, deaf bimodal bilinguals were slower to reject semantically unrelated word pairs, but were faster to accept semantically related pairs, relative to pairs of words whose ASL translations did not overlap. In contrast, hearing unimodal bilinguals did not show differences in response time across conditions, suggesting that the reaction-time differences were driven by the co-activation of ASL and written English in the bimodal bilinguals.

Complementary effects have been found when testing highly proficient, *hearing* speech-sign bilinguals (Giezen, Blumenfeld, Shook, Marian, & Emmorey, 2015; Shook & Marian, 2012; Villameriel, Dias, Costello, & Carreiras, 2016). For example, in Van Hell et al. (2009), hearing Dutch-Sign Language of the Netherlands (SLN) bilinguals performed a word-verification task, in which participants judged whether visually-presented signs and images were synonymous. These Dutch-SLN bilinguals were slower to reject mismatched pairs when the Dutch translation of the sign and the Dutch picture label overlapped phonologically, suggesting that the bilinguals activated Dutch when processing SLN. Unlike the Van Hell et al. (2009) study, where bimodal bilinguals showed intrusion from their more dominant spoken language, Shook and Marian (2012) tested ASL-English bilinguals in an English-speaking environment. Participants viewed displays of four images and heard instructions, in English, to click on particular items. Bimodal bilinguals were found to look more at items whose ASL translation overlapped phonologically with the translation of the target item, relative to both monolingual English speakers and to concurrently displayed items that did not overlap in either English or ASL. Critically, even though the task was performed in their more dominant English language and did not require participants to utilize their ASL knowledge, bimodal bilinguals nevertheless accessed their sign-language.

Taken together, there is strong evidence that bilinguals activate both of their languages quickly, automatically, and across modalities, which further suggests extensive interactivity between the two languages even when the input does not directly map onto the representations of the unused language. This process represents *covert* co-activation of the bilingual's languages. In contrast to *overt* co-activation, where ambiguity in the input itself causes non-selective access to words of both a bilingual's languages, *covert* co-activation occurs in linguistically unambiguous environments, and relies upon features *within* the language system, such as direct connections between cross-language translations or mediation through a shared semantic system. However, the possibility remains that the effects seen in bimodal and different-script bilinguals could be driven not by general mechanisms of the language system, but by something unique to the particular groups or tasks. Previous research on cross-linguistic lexical priming has shown that whether two languages share an orthography can impact the degree to which languages co-activate. For example, asymmetrical priming effects (where L1 words prime L2 words, but L2 words do *not* prime L1 words) have been found in masked-priming studies that use different scripts (Finkbeiner, Forster, Nicol, & Nakamura, 2004; Gollan, Forster, & Frost, 1997; Jiang and Forster, 2001); however, L2-L1 priming effects have been observed in balanced bilinguals whose languages share an alphabet (see Schoonbaert, et al., 2009, for a review). Additionally, research measuring ERP responses during a masked priming task with cross-script bilinguals (L1 Japanese and L2 English) has shown significant N250 and N400 effects for L1-L2 translation priming, but not for L2-L1 translation priming (Hoshino, Midgley, Holcomb, & Grainger, 2010). Priming from L1 to L2 in *different*-script bilinguals also shows earlier ERP responses (on the order of 100 ms) relative to L1-L2 priming for *same*-script bilinguals (French-English; Midgley, Holcomb, & Grainger, 2009). Together, these studies indicate that cross-script bilinguals may process translations differently than same-script bilinguals.

Similar to cross-script bilinguals, bimodal bilinguals may process translations differently from unimodal bilinguals, due to the structure of ASL and the relationship between ASL and English. Consider, for example, two common ways that ASL users might sign the word "bus." First, signers can mimic the act of pulling the cord on a bus (to indicate to the driver to stop), which represents a conceptual property of the bus itself, and/or the act of riding the bus. The existence of iconographic signs may boost connections between lexical items and semantic representations. Second, signers can produce the word 'bus' using the fingerspelled letters 'b-u-s', the same spelling as in English. Because ASL does not have a written system, and so relies entirely on English spelling when writing or fingerspelling signs, signs and spoken words may share a single orthographic representation, which could strengthen the connection between translation equivalents. As a result of these potential effects, bimodal bilinguals may be *more* likely to show covert co-activation because the connections between the signs and the orthographic or conceptual representations themselves may be stronger. In addition, bimodal bilinguals may mouth translations during sign production, which may further strengthen connections between translation equivalents. If, in fact, the bimodal bilingual represents a unique type of bilingual, then the pattern of activation seen in bimodal research may not apply to unimodal groups.

2. The current study

The current study will examine whether the two languages are co-activated when auditory input maps to unambiguous targets in a single language, as a result of cascading activation flowing both between and within languages in real time. While previous studies have shown co-activation of translation equivalents in the other language (target *shovel* activates translation *pala*), as well as activation of covert competitors in different-script and bimodal bilinguals (e.g., Wu & Thierry, 2010a; Shook & Marian 2012), the present research explores whether bilinguals of two spoken languages show cascading activation from the co-activated translation equivalents to phonologically-overlapping items in the non-target language (co-activated translation *pala* in turn activates phonological cohort *pato*), and further back to the translation equivalent of the phonologically-overlapping item (*pato* then activates its translation *duck*), indicating an even greater degree of interactivity than previously established.

Given the covert, cross-linguistic activation seen in both different-script and bimodal bilinguals, observing evidence of covert co-activation in English-Spanish bilinguals would provide further support that mechanisms beyond phonological ambiguity or overlap in the input can drive language interactivity. Recent research in computational modeling may provide a window into those possible mechanisms. For example, the *Bilingual Language Interaction Network for Comprehension of Speech* (BLINCS; Shook & Marian, 2013) suggests that auditorily-presented words can activate their translation equivalents through either semantic feedback or direct connections between lexical items in unimodal same-script bilinguals (e.g., Spanish-English). The BLINCS model predicts that after spoken words co-activate translation equivalents, these co-activated translation equivalents subsequently spread activation to their phonological cohorts in the non-target language, which then in turn spread activation to their translation equivalents in the target language, resulting in a cascading network of within- and between-language co-activation during bilingual spoken language comprehension. We will test this prediction empirically and, if confirmed, these results would demonstrate extensive spreading interactivity in the bilingual language system during spoken comprehension. Importantly, this pathway to cross-linguistic co-activation is not reliant upon form overlap.

Based on both computational evidence and empirical studies with different-script and bimodal bilinguals, we expect that same-script, unimodal bilinguals will also show covert co-activation during speech comprehension. Specifically, when asked in English to click on an image of a duck, English-Spanish bilinguals (but not monolinguals) will look more to the image of a shovel than to unrelated distractors, because the English word *duck* activates its Spanish translation *pato*, which in turn co-activates the Spanish phonologically-overlapping word *pala*, meaning *shovel*. Such findings would suggest an extended degree of interactivity in the language system during speech comprehension even when the bottom-up information in the signal does not map onto both languages.

3. Methods

3.1 Participants

Fifteen English monolinguals (12 female; M_{age} = 21.2 yrs) and 15 English-Spanish bilinguals (11 female; M_{age} = 22.5 yrs) participated in the study. To be included in the study, bilingual participants were required to score 70% or greater on a Spanish/English picture naming task; monolingual participants were excluded if they indicated any experience with Spanish on the *Language Experience and Proficiency Questionnaire* (LEAP-Q; Marian, Blumenfeld, & Kaushanskaya, 2007). Within the bilingual group, nine participants (60%) reported earlier acquisition of English, and six participants reported simultaneous acquisition; all bilinguals were early learners of both languages (i.e., acquisition before 8 years of age). For more information about the participants, see Table 1. English monolinguals showed statistically higher English abilities relative to the bilinguals, as reflected by higher

Table 1. Participant information

	Monolinguals (*N* = 15)		**Bilinguals (*N* = 15)**		
	Mean	**SD**	**Mean**	**SD**	
Age (years)	21.2	1.9	22.5	5.0	
Non-verbal IQ (WASI)	108.3	9.1	108.2	7.4	
Vocabulary (PPVT)	116.7	8.9	106.5	12.6	*
Working memory (CTOPP DS)	17.7	2.4	17.7	2.6	
Working memory (CTOPP NWR)	13.5	2.9	12.9	2.1	
Simon effect	46.2	13.5	49.3	17.1	
English proficiency	9.8	0.4	9.1	0.9	*
English age of acquisition (years)	0.5	0.7	4.1	2.1	*
Spanish proficiency	–	–	8.6	0.7	
Spanish age of acquisition (years)	–	–	1.5	1.4	

Note.
* indicates a significant difference at $p < 0.05$. WASI = Wechsler Scale of Abbreviated Intelligence; PPVT = Peabody Picture Vocabulary Test; CTOPP DS: Comprehensive Test of Phonological Processing, Digit Span; CTOPP NWR: Comprehensive Test of Phonological Processing, Non-Word Repetition

self-reported English proficiency (an average of Speaking, Understanding, and Reading abilities) and better performance on the PPVT (Dunn & Dunn, 1997); additionally, the monolinguals learned English earlier than the bilingual participants. However, the difference in vocabulary scores is unlikely to influence the results in the present study, due to the fact that we explicitly measured whether our participants knew the words that were critical to the experiment via a naming task that was performed at the end of the experimental session.

3.2 Materials

3.2.1 *Visual stimuli*

Forty target items were selected; twenty in English and twenty in Spanish. Each target word was paired with a covert phonological competitor whose translation phonologically overlapped with the translation of the target. For example, the words "duck" and "shovel" constitute a target-competitor pair, because the Spanish translations (*pato* and *pala*, respectively) overlap in phonology. Half of the forty target-competitor pairs were English words whose Spanish translations overlapped (e.g., duck/*pato* – shovel/*pala;* Spanish-covert items), and half were Spanish words whose English translations overlapped (e.g., *dulces*/candy – *vela*/candle; English-covert items). An additional 80 items were selected to serve as the two unrelated distractor items in the experimental trials. Of the twenty Spanish-covert pairs, the average phoneme length was 6.35 ($SD = 2.03$) for targets, 6.00 ($SD = 1.52$) for competitors, and 5.60 ($SD = 2.50$) for fillers; targets and competitors overlapped in 2.9 phonemes and targets and fillers overlapped in 1.6 phonemes (paired $p < 0.001$). For the twenty English-covert pairs, the average phoneme length was 5.4 ($SD = 1.82$) for targets, 5.95 ($SD = 2.06$) for competitors, and 5.05 ($SD = 2.13$) for fillers; targets and competitors overlapped in 2.45 phonemes, and targets and fillers overlapped in 0.6 phonemes (paired $p < 0.001$).

Within each condition, target, competitor, and filler items were matched on word frequency in English (SUBTLEXUS; Brysbaert & New, 2009) and Spanish (SUBTLEX-ESP; Cuetos, Glez-Nosti, Barbon, & Brysbaert, 2011), and the number of phonological and orthographic neighbors in English (N-Watch; Davis, 2005) and Spanish (BuscaPalabras; Davis & Perea, 2005). A full list of stimuli for each condition is provided in the appendices.

Black and white line drawings were obtained for each item from the International Picture Naming Database (IPNP; Bates, et al. 2003) or from Google Images. Images obtained from the IPNP were selected based on high naming consistency, while pictures obtained from Google Images were independently normed by 20 English monolinguals and 20 Spanish-English bilinguals on Amazon's

Mechanical Turk (https://www.mturk.com). Naming reliability in English was 84.4% (*SD* = 8.7), and in Spanish was 85.2% (*SD* = 14.3).

Images were presented in the four corners of a 3x3 square (1440 x 1440 pixels) grid. The location of the target was counterbalanced across trials. The competitor always appeared in a quadrant adjacent to the target (i.e., either to the right/ left of the target, or above/below the target, never in opposite corners; with location counterbalanced across trials) in order to maintain consistent visual distance between the target and competitor across trials. Pictures appearing in the same display were controlled for visual similarity along the dimensions of shape (i.e. a pencil and a finger did not appear in the same display), saturation (i.e. no single image had areas that were noticeably darker), and line thickness.

Following the experiment, participants were asked to name target and competitor pictures in both English and Spanish. Trials in which the participant provided an alternate name for either the target or competitor that resulted in no phonological overlap between critical items were excluded from further analysis. In addition, participants were asked to rate how semantically related they thought each critical pair was on a scale of 1 (Completely Unrelated) to 9 (Completely Related). Spanish-covert pairs had an average rating of 2.10 (*SD* = 1.17), and English-covert pairs had an average rating of 2.01 (*SD* = 1.06), $p > 0.1$. Based on the results of the semantic-relatedness test, two pairs were rated above 5.0 (waterfall-*cascada* / watering can-*regadera* and fan-*ventilador* / window-*ventana*) and subsequently removed from all analyses.

3.2.2 *Auditory stimuli*

The 40 target items (20 English, 20 Spanish) were recorded by a male bilingual speaker of Spanish and English. Each word was recorded at 44.1 KHz and was amplitude normalized. The bilingual speaker was independently rated by 10 bilingual English-Spanish speakers for accentedness on a scale of 1 (No Accent) to 4 (Strong Accent) using English and Spanish recordings of the Rainbow Passage (Fairbanks, 1960). The speaker was rated as having very little accent in either English (*M* = 1.5, *SD* = .8) or Spanish (*M* = 1.2, *SD* = 0.4).

3.3 Procedure

After consent was obtained, participants were seated approximately 80 cm away from a computer screen (2560 x 1440 resolution), were fitted with closed-back headphones, and placed their chins into a chin-rest for the duration of the eye-tracking experiment. Participants eye-movements were tracked using an Eyelink 1000 eye-tracking system recording at 1,000 Hz (1-ms sampling resolution).

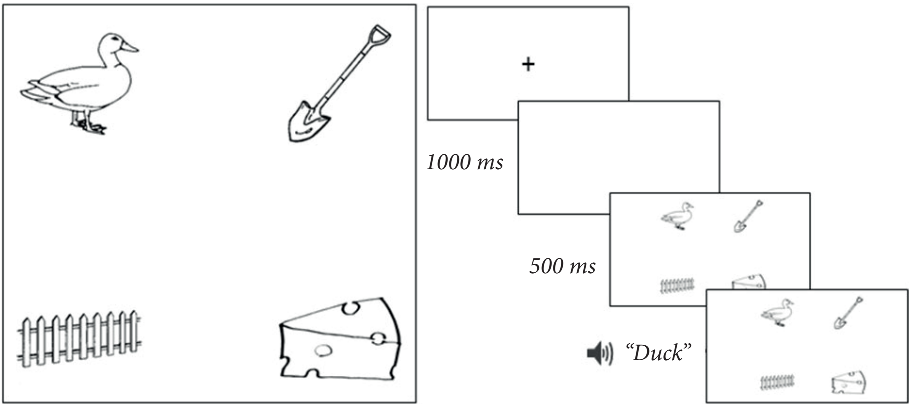

Figure 1. Example of critical trial and trial procedure. Participants heard the word "duck" over headphones and were required to click on a target item in the presence of a covert cross-linguistic competitor and two unrelated fillers. In the example, the target word "duck" is heard. The Spanish translation of duck, "pato," overlaps phonologically with the Spanish label for another object in the display, shovel (Spanish "pala"). No Spanish is used at any time during the trial.

The experiment began with four practice trials (using novel stimuli) to familiarize the participants to the task. Each trial began with the display of a fixation cross, which participants clicked to advance the screen. Once the fixation cross was clicked, participants were presented with a blank white screen for 1,000 ms, after which the search display (3 x 3 grid containing the target, two unrelated distractor items, and either a competitor or control item) appeared. After a 500 ms delay, participants heard a word and were required to click on the object that was best represented by that word using the computer mouse (see Figure 1 for trial and procedure). Stimuli presentation was controlled via PsychToolbox.

The order of presentation was pseudo-randomized such that targets and competitors appeared in each quadrant an equal number of times and the target item did not appear in the same quadrant for more than three consecutive trials. Half of the participants received the trials in reverse order, and in the bilingual group, half were presented with the English (Spanish-covert) condition first, while the other half received the Spanish (English-covert) condition first. An additional 120 filler trials (60 Spanish and 60 English), which consisted of a target item and three unrelated distractors, were recorded by the same speaker who recorded the experimental stimuli, and were included to mask the purpose of the study for participants, totaling 160 trials for the bilingual participants and 80 trials for the monolingual participants.

3.4 Data analysis and design

The dependent measures recorded during the experiment included the proportion of eye-fixations to target, competitor, and distractor items, mouse-click reaction times, and accuracy. Eye-fixations were defined as any eye-movement event where the participant maintained a consistent gaze at a given spatial location on the screen for greater than 100 ms; fixations less than 100 ms in duration were not included in the analysis. For the time-course analyses, fixations were collapsed into 10 ms bins, and the average fixation to each item at each 10 ms bin was recorded; fixations not directed at any item were included in the calculation, allowing for a robust capture of the time-course of activation. In the fixation analyses, we are primarily interested in comparing fixations to items that compete with the target relative to the adjacent unrelated distractor in the same display; thus, only fixations to one of the four items on the display were included in the analyses. If hearing the target word activates both its translation, and lexical items that are phonologically related to that translation, then bilinguals should fixate more on the competing item relative to an unrelated item in the display.

4. **Results**

4.1 Accuracy and reaction time

Both bilingual and monolingual participants were highly accurate, selecting the target item 95% of the time on average. The mean reaction time was 1,687 ms ($SD = 188$ ms) for monolinguals and 1,729 ms ($SD = 202$ ms) for bilinguals ($p > 0.1$). Trials with reaction times that were greater than 2.5 SDs from the mean were removed from analysis, totaling approximately 1.9% of the data.

4.2 Time course analyses

4.2.1 *Bilingual competition in English and Spanish*

To examine whether English-Spanish bilinguals showed evidence of covert cross-linguistic competition in their two languages, a growth-curve analysis (GCA) was performed on the time window starting at target word onset and ending at 1700 ms post-onset; the terminal time-point was determined by rounding the average reaction time across all participants (1,708 ms) to the nearest 100 ms. This long window was selected because the degree to which co-activation effects may be time-locked to speech is less clear than in the case where phonological ambiguity drives competition. Thus, the initial analyses would be able to capture later effects. The effect of time on fixations was modeled with orthogonal polynomials (see Mirman, 2014 for commentary regarding the significance of the various polynomial terms). To capture how the current language of presentation and the item type modulated changes to fixations over time, the model included interactions of the polynomials with fixed effects of Item Type (Competitor, Adjacent filler), Language (English, Spanish), and Language Order (English-condition first, Spanish-condition first), along with their interactions. Random intercepts and slopes for the orthogonal polynomials representing changes over time were included for participants and the nested effects of participant by within-participant factors (Language, Item Type, and Language Order).[1]

Significant main-effects were found at the intercept term for Item Type ($Est. = -0.016$, $SE = 0.01$, $t = -2.08$, $p < 0.05$) and Language ($Est. = 0.02$, $SE = 0.07$, $t = 2.88$, $p < 0.05$). No other main effects or interactions were found (all $ps > 0.1$). The main effect of Item Type indicates that the bilinguals looked more at the covert competitors than at the adjacent fillers overall (see Figure 2, panel A); the main effect of language indicates that bilinguals looked more at both competitors and fillers in the Spanish condition, relative to the English condition. The lack of a significant interaction between Item Type and Language suggests that bilinguals' experienced covert, cross-linguistic competition to a similar degree in both of their known languages. The overall greater proportion of fixations in the Spanish condition may reflect the participants' slightly lower Spanish proficiency, relative to English. Because Spanish was their weaker language, they may have been more likely to study all the display items early in the trial in order to determine which item corresponded to the auditory cue. Importantly, this did not influence the degree to which they experienced cross-linguistic competition (as evidenced by the non-significant Item Type x Language) interaction, nor did it have an impact on their overall reaction time in selecting the item ($M_{English}$: 1,649 ms, $M_{Spanish}$: 1,732 ms, $p > 0.1$). Because the effect of Language did not influence the degree of cross-language competition in bilinguals, the bilingual participants' performance was collapsed across language conditions for all further analysis.

1. The model included Language Order in both fixed- and random-effects terms in order to control for its potential effect on the fixations. However, the small number of observations, due to the limited sample size in each order group, makes interpreting this effect not possible.

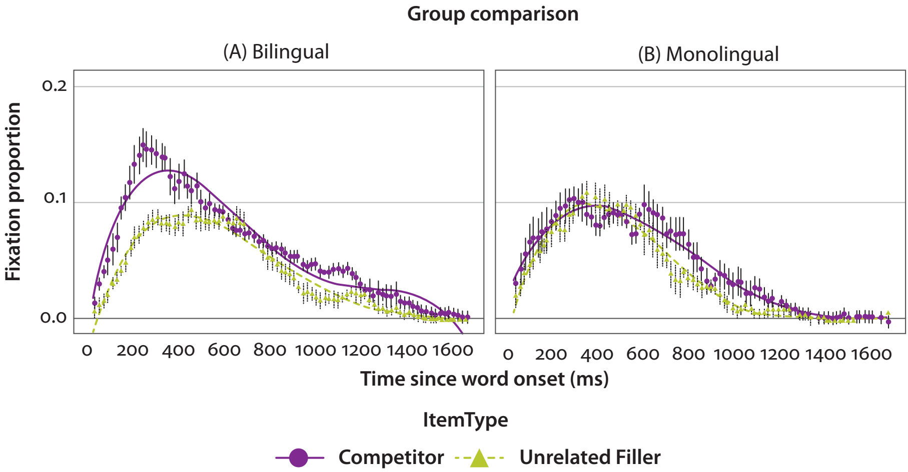

Figure 2. Time course of processing for (A) English-Spanish Bilinguals and (B) Monolinguals. The curves represent the growth curve model that was fitted to the data – the solid line represents competitors and the dashed line represents the filler items. Means and standard errors for each fixation point are represented as circles with solid error bars for competitors, and triangles with dashed error bars for fillers.

4.3 Cross-language competition

To further examine whether bilinguals showed covert cross-linguistic competition, their performance on the Visual World Task was compared to monolingual English speakers. A growth-curve analysis (GCA) was performed on the time window starting at target word onset and ending at 1700 ms post-onset. To capture whether bilinguals and monolinguals differed in their fixation patterns to competing items relative to unrelated fillers, the model included interactions of the polynomials with fixed effects of Item Type (Competitor, Adjacent filler) and Group (English-Spanish Bilingual, English Monolingual), along with their interactions. Random intercepts and slopes for the orthogonal polynomials representing changes over time were included for participants and the nested effects of participant by within-participant factors (Item Type).

The GCA revealed a significant interaction between Item Type and Group at both the intercept (*Est.* = 0.012, *SE* = 0.01, $t = 2.73$, $p < 0.05$) and quartic term (*Est.* = −0.17, *SE* = 0.057, $t = -3.06$, $p < 0.01$). Visual inspection of the graph indicated that the cross-linguistic competition effects emerged early in the time course, consistent with the significant interaction at the quartic term, which is thought to express differences at the tails of the model curve, and with previous research indicating that covert competition occurs within the first 500 ms following target onset (Giezen et al., 2015; Shook & Marian, 2012; Thierry & Wu, 2007). Therefore, to ensure that the relationship between bilingual status and covert, cross-linguistic competition was accurately captured, follow-up analyses were performed on the smaller time window of 0 – 500 ms post target onset.

The overall GCA, using the same fixed- and random-effects as with the larger time window, revealed a similar pattern of results. A significant Item Type x Group interaction was found at the intercept term (*Est.* = 0.04, *SE* = 0.01, $t = 3.16$, $p < 0.01$). Significant main effects were found at the quadratic term for both Item Type (*Est.* = 0.12, *SE* = 0.04, $t = 2.85$, $p < 0.01$) and Group (*Est.* = 0.11, *SE* = 0.05, $t = 2.14$, $p < 0.05$), along with a marginal interaction (*Est.* = −0.11, *SE* = 0.06, $t = -1.84$, $p = 0.07$). Follow-up analyses looking at each group separately revealed significant main effects for Item Type in the bilingual group at both the intercept (*Est.* = –.04, *SE* = 0.01, $t = -5.09$, $p < 0.01$) and quadratic terms (*Est.* = 0.12, *SE* = 0.03, $t = 3.48$, $p < 0.01$). For monolinguals, no significant main effects were found (all *ps* > 0.1). These results indicate that bilinguals activated competitor items to a greater extent than unrelated adjacent fillers, while monolinguals showed no evidence of competition (see Figure 2, panel B). When the groups were compared on each item type separately, no main effects were found for filler items (all *ps* > 0.1). Conversely, a main effect of Group was found for competitor items at the quadratic term (*Est.* = 0.01, *SE* = 0.04, $t = 1.95$, $p = 0.05$). These results indicate that bilinguals showed more fixations of competitors early in the processing window, relative to monolinguals, but the two groups did not differ in the processing of filler items.

4.4 Overall fixation analyses

In addition to growth-curve analyses, cross-linguistic competition was analyzed via mixed-effects modeling, using the *lme4* package in R statistical computing software. To capture cross-linguistic competition within our bilingual group, we constructed a mixed-effects model (MLM) that included random intercepts and slopes on the fixed effects of Item Type (Competitor, Adjacent filler) and Language (English, Spanish). Intercept terms of Subjects and Items were included as random-effects, accounting for the contribution of both individual subjects and individual items to the pattern of eye-fixations[2]. In addition, because lexical frequency is known to influence eye-movements in the Visual World Paradigm (e.g., Magnuson, Dixon, Tanenhaus, & Aslin, 2007), we included random-intercepts of English and

2. A second model was also constructed with the slope term of Item Type on the random effect of Subjects and Items. The more complex slope model did not fit the data significantly better than the less complex intercept model ($\chi^2(14) = 0.47$, $p > 0.1$), and so the intercept model is reported here.

Spanish lexical frequency for the items. Analyses were again performed over the time-window from 0 ms to 500 ms post target-word onset. Consistent with the growth-curve analyses results reported above, the results of the MLM indicate that bilinguals activated the competitor items to a greater extent than unrelated filler items, and that the difference between item looks was not influenced by the language of presentation. Specifically, the MLM revealed a main effect of Item Type (*Est.* = 0.09, *SE* = 0.04, $t = 2.17$, $p < 0.05$), and no main effect of, or interaction with, Language (*ps* > 0.05). Because the bilinguals did not show differences in the pattern of cross-linguistic competition for Spanish versus English, the bilinguals' English and Spanish conditions were collapsed when comparing the bilingual and monolingual groups. We constructed an MLM, with random intercepts and slopes on the fixed effects of Item Type (Competitor, Adjacent filler) and Group (Bilingual, Monolingual). Intercept terms of Subjects and Items were included as random-effects, accounting for the contribution of both individual subjects and individual items to the pattern of eye-fixations. The MLM (Figure 3) revealed a significant interaction between Item Type and Group (*Est.* = −0.10, *SE* = 0.05, $t = -2.18$, $p < 0.05$). Follow-up analyses on each individual group revealed that bilinguals made significantly more looks (*Est.* = 0.10, *SE* = 0.03, $t = 4.05$, $p < 0.01$) to competing items (*M* = 29.7%, *SE* = 1.9%) relative to unrelated fillers (*M* = 19.3%,

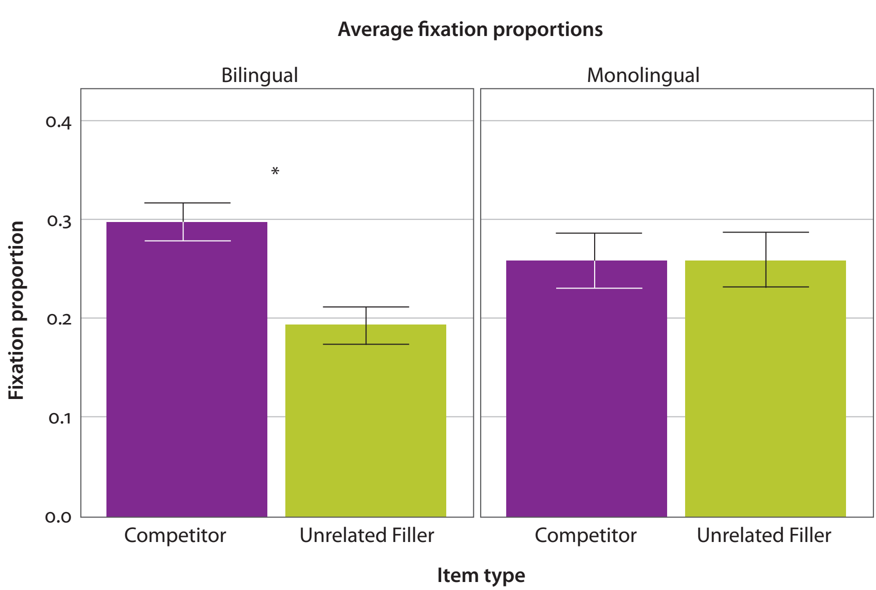

Figure 3. Average fixation proportions for Bilingual and Monolingual participants based on the first 500 ms post word-onset. Purple bars represent looks to competitors and yellow bars represent looks to unrelated filler items. Error bars represent one standard error of the mean.

SE = 1.7%), but monolinguals fixated both competitors (*M* = 25.7% *SE* = 3.0%) and fillers (*M* = 25.8% *SE* = 2.9%) similarly, $p > 0.1$.

5. Discussion

In the current study, we found evidence that bilinguals activated both languages when the signal itself did not provide direct input to the unused language. For example, when asked in English to click on an image of a duck, English-Spanish bilinguals looked more to the image of a shovel than to unrelated fillers, because the Spanish translations of the words duck and shovel (*pato* and *pala*, respectively) overlap phonologically. Likewise, when asked to click on an image of a *dulces* (candy), the bilinguals looked more at the image of a candle. Our results are consistent with previous research on different-script bilinguals and bimodal bilinguals, suggesting that there is an impressive amount of interactivity in the language system, and that a unimodal bilingual's unused language can be activated not only through direct, bottom-up input (e.g., Marian & Spivey, 2003a, b), but also through connections in the lexical-semantic system, such as feedback from shared semantic representations, or direct connections between translation equivalents at the lexical level, both of which result in cascading activation to phonological cohorts of the un-heard target translation.

Our findings provide compelling support for interactivity in the bilingual language system. Specifically, the finding that English-Spanish bilinguals exhibit covert competitor activation, similar to previous research with both bimodal (Morford et al., 2011; Shook & Marians, 2012) and different-script (Thierry & Wu, 2007; Wu & Thierry, 2010) bilinguals, suggests that covert cross-linguistic interaction is not limited to unique cases of bilingualism. Together, research on covert competition across various types of bilinguals creates a compelling case for language co-activation even when bottom-up mediation is limited. A parsimonious account of covert co-activation would suggest that these distinct bilingual groups utilize the same mechanisms when accessing covert competitors during language processing. Under such an account, differences seen in processing may be a matter of degrees rather than design. For instance, asymmetrical effects of L1-L2 translation in different-script bilinguals (e.g., Hoshino et al. 2010) may be due to differences in typology rather than to different mechanisms of processing. Likewise, the strength of connections between translations may differ in bimodal bilinguals, but the same basic mechanism of semantic feedback or lateral connections between lexical items may still apply.

Furthermore, our results are also consistent with research on monolingual language processing. English monolinguals have been shown to activate lexical items that are semantically related to phonological competitors in the visual world paradigm (Yee & Sedivy, 2006; Yee & Thompson-Schill, 2007). For instance, monolinguals will preferentially fixate a picture of a key given the word "log," because the word "log" activates the lexical and semantic representations of the phonological competitor "lock," which in turn activates semantic associates like "key." That the pattern of substantial interactivity required for covert, cross-linguistic activation is consistent with patterns seen across diverse groups of language users may indicate that this high level of connectivity in the language system may in fact be a general property of linguistic processing.

Along with previous behavioral research, the pattern of results seen in the present study closely matches patterns predicted by the BLINCS model (Shook & Marian, 2013). Within the BLINCS model, interactions between items that are unrelated in one language, but whose translations are highly overlapping, are primarily driven by feedback from the semantic level (much as one would predict from the work of Yee & Sedivy, 2006). As the word "duck" is presented to the model, activation spreads upward to the lexical representation that matches the phonological input, and subsequently to the corresponding semantic representation; the semantic node for "duck" is able to feed activation back down to the lexical representations that correspond to that meaning in *both* languages (i.e., to both duck and *pato*). As *pato* becomes activated at the lexical level, it in turn can activate phonologically similar lexical entries like *pala*, which results in stimulation of the semantic representation of "shovel," its English translation equivalent. The ultimate result of this process is that items that are not related to the phonology of the input itself, but only to the *meaning* of the input, are activated in parallel.

However, drawing upon feedback from the semantic level is not the only method by which covert, cross-linguistic activation may occur. The BLINCS model also posits a second possible mechanism by which covert co-activation can occur; rather than being driven by the top-down feedback of a shared conceptual representation, translation equivalents may instead have lateral, excitatory connections at the level of the lexicon, formed by repeated co-activation of the two translations. Under this alternative, as participants hear "duck" and activate the matching lexical item in English, activation is passed along a direct connection to "*pato*" in the lexical space of the language system. As "*pato*" becomes more active, it in turn activates phonological cohorts in both languages, resulting in the access of phonologically similar items such as "*pala*" (English "shovel").

Critically, within the BLINCS model either mechanism (feedback from semantic representations or direct translation links), or both mechanisms working in concert, may drive the pattern of covert co-activation observed in the present study. Additionally, the Revised Hierarchical Model (RHM; Kroll & Stewart, 1994) suggests that the relative influence of either mechanism could depend on the relative proficiency of the two languages. Specifically, those with lower L2 proficiency may be more likely to rely upon translation level links, while those with higher proficiency may rely more on semantic mediation. The RHM would suggest that the effects observed in the bilinguals in the current study, who were highly proficient in their two languages and learned both early in life, may have been more driven by semantic feedback than translation links. However, the present findings also lend support to a direct translation account. For instance, the BLINCS model predicts that co-activation would occur earlier in the time-course via direct translation links relative to semantic mediation; interestingly, the onset of semantic competition effects seen in Yee & Sedivy (2006; target – *logs*, competitor – *key*) occurred slightly later post word onset than the covert competition observed herein. Ultimately, the present study cannot dissociate between these two potential mechanisms, or the relative influence either may have on covert competition in bilinguals.

Both the semantic feedback and translation link accounts rely upon online co-activation of covert competitors. Alternatively, a method by which the covert competitors can co-activate without requiring online activation of the non-target language has recently been proposed by Costa et al. (2016). Under the learning account of co-activation, the consistent co-activation of *duck* and *shovel*, by virtue of the cascading activation described above (i.e., *duck* activates its semantic representation, which activates both *duck* and *pato*, which activates phonological neighbor *pala,* resulting in the activation of *shovel*) results in the English words *duck* and *shovel* inheriting the co-activation of their Spanish translations, in a sense, all within the English lexicon of the bilingual. Here, rather than co-activation being driven by automatic, online translation, co-activation is the product of long-term bilingual experience fundamentally altering the connections within the target language. Such within-language associative connections are possible within the current BLINCS architecture and provide an avenue for future research into covert competitor activation. While both online co-activation and connections established during learning likely drive interactivity in the bilingual language system, future research will need to find a way to dissociate the two mechanisms in order to properly trace the source of the effects.

There is yet another possible mechanism that could play a role in covert competition, which does not rely on the linguistic input at all. Recent research suggests that when viewing objects in a display, speakers automatically access labels for those objects (Wu et al., 2013; Chabal & Marian, 2015; Mishra & Singh, 2015). For example, Marian and Chabal (2015) used a non-linguistic task in which English-Spanish bilinguals saw a single image and later had to select that same image from an array; in critical trials, the labels of other images in the array shared phonological overlap with the target in either English (target label: clock, competitor label: clouds), or Spanish (target label: *reloj* / clock, competitor label: *regalo* / present). The authors found that both monolingual English and bilingual English-Spanish viewers fixated more on the English competitor, while bilinguals were also more likely to fixate on the Spanish competitor, relative to unrelated filler items. Crucially, the items were not pre-labeled nor was any linguistic input provided during the picture-matching task. The authors concluded that their participants activated the labels for the items in the display automatically. Such a mechanism may play a role in the results observed in the present study; however, de-coupling the influence of unambiguous single-language input from the visual input alone is a matter for future research.

Exploring these potential mechanisms is critical not only to determining the architecture of the bilingual language system, but also for establishing the generalizability of the interactivity necessary for covert co-activation to occur. If lateral translation links exclusively guide covert co-activation, then one could reasonably conclude that the highly interactive nature of covert co-activation is a product of learning and managing two languages, because monolinguals by default cannot create translation links. This would suggest that the interactivity seen in the present study is unique to bilinguals. Thus, it is crucial that future work focuses on exploring and delineating the impact of these distinct mechanisms in order to more fully understand language processing.

One possible limitation of our findings arises from the fact that bilinguals were exposed to both languages across different experimental blocks. Several studies have highlighted the mediating effect that prior language context can have on language co-activation (Marian & Spivey, 2003a; Mercier, Pivneva, & Titone, 2016; Wu & Thierry, 2010b). Thus, it is possible that the covert competition effects seen in the present study were influenced by prior context across language blocks. However, the exact nature of this effect is not clear. On the one hand, Marian & Spivey (2003a) found that providing linguistic context in the form of L2 music and communication prior to an eye-tracking study increased cross-linguistic competition in bilinguals. In contrast, Mercier et al. (2016) found that English-French bilinguals showed *less* competition from French in an English visual-world task (e.g., target: field, competitor: girl, French *fille*) if they had previously completed a spontaneous word production task in French, suggesting that recent experience with the non-target language actually decreased cross-linguistic co-activation. Though the precise impact recent language context may have on processing is varied, it is important to consider the possible influence of language context when interpreting the current findings.

In summary, the present study provides compelling evidence that bilinguals access and activate their unused language during speech comprehension through cascading spreading activation both across and within languages, even when the bottom-up information in the signal does not directly correspond to the unused language. From a broad language processing standpoint, our results showcase that while bimodal bilinguals, unimodal bilinguals, and monolinguals differ in the ways that they use and process language, these varied groups of language users all demonstrate substantial interactivity during language processing.

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Appendix 1. English target, competitor, and adjacent filler stimuli

English speech, covert Spanish overlap condition

Target		Competitor		Adjacent filler	
English	**Spanish**	**English**	**Spanish**	**English**	**Spanish**
Whale	ballena	cane	bastón	skate	patín
Diver	buzo	mailbox	buzón	tongue	lengua
Chain	cadena	horse	caballo	wheelchair	silla de ruedas
Bell	campana	shirt	camisa	wine	vino
Pumpkin	calabaza	sock	calcetín	wrench	llave
Mirror	espejo	handcuffs	esposas	rope	cuerda
Suitcase	maleta	hose	manguera	frog	rana
Bone	hueso	egg	huevo	fox	zorro
Umbrella	paraguas	dove	paloma	zipper	cremallera
Apple	manzana	butter	mantequilla	knight	caballero
Windmill	molino	fly	mosca	shoulder	hombro
Duck	pato	shovel	pala	fence	cerco
Drill	taladro	heel	tacón	eyebrow	ceja
Fan	ventilador	window	ventana	hand	mano
Puzzle	rompecabezas	knee	rodilla	sunflower	girasol
glass	vaso	cow	vaca	wolf	lobo
shoe	zapato	carrot	zanahoria	butterfly	mariposa
purse	bolsa	mouth	boca	toys	juguetes
rocket	cohete	swing	columpio	acorn	bellota
thumb	pulgar	octopus	pulpo	celery	apio

	Target		Competitor		Adjacent filler	
	English	**Spanish**	**English**	**Spanish**	**English**	**Spanish**
Frequency	2.86 (0.37)	2.62 (0.41)	2.91 (0.52)	2.62 (0.50)	2.80 (0.70)	2.65 (0.75)
Orthographic	5.90	3.75	5.20	3.80	5.53	5.00
Neighborhood	(6.49)	(5.83)	(5.20)	(5.50)	(6.50)	(5.34)
Phonological	13.11	6.15	11.95	5.85	11.90	4.97
Neighborhood	(10.85)	(9.38)	(9.93)	(7.79)	(9.55)	(6.51)

Means (Standard Deviations) for Target, Competitor, and Distractor items. No differences were found between conditions (*p*s > 0.1).

Appendix 2. Spanish target, competitor, and adjacent filler stimuli

Spanish speech, covert English overlap condition

Target		Competitor		Adjacent filler	
Spanish	**English**	**Spanish**	**English**	**Spanish**	**English**
cuerno	antler	hormiga	ant	balsa	raft
canasta	basket	murciélago	bat	sombrero	hat
cerebro	brain	puente	bridge	rey	king
dulces	candy	vela	candle	asador	barbecue
tambor	drum	vestido	dress	oso	bear
oveja	sheep	escudo	shield	hebilla	buckle
pistola	gun	canalón	gutter	arból	tree
encendedor	lighter	rayo	lightning	inodoro	toilet
imán	magnet	cerilla	match	elote	corn
cerdo	pig	cuadro	picture	chimenea	fireplace
sonaja	rattle	mapache	raccoon	tocino	bacon
codo	elbow	ascensor	elevator	puerta	door
payaso	clown	nube	cloud	tronco	log
miel	honey	colibrí	hummingbird	perro	dog
caracol	snail	mono de nieve	snowman	foco	lightbulb
linterna	flashlight	bandera	flag	mecedora	rocking chair
bufanda	scarf	tornillo	screw	perro caliente	hot dog
sapo	toad	dedo	toe	caja	box
cascada	waterfall	regadera	watering can	cinta	tape
peluca	wig	bruja	witch	faro	lighthouse

	Target		Competitor		Adjacent filler	
	English	**Spanish**	**English**	**Spanish**	**English**	**Spanish**
Frequency	2.55 (0.54)	2.74 (0.69)	2.91 (0.52)	2.62 (0.50)	2.72 (0.69)	2.84 (0.73)
Orthographic	2.55	4.55	5.20	3.80	4.08	4.88
Neighborhood	(3.84)	(4.21)	(5.20)	(5.50)	(5.28)	(5.63)
Phonological	3.37	10.50	11.95	5.85	5.11	11.14
Neighborhood	(4.31)	(7.32)	(9.93)	(7.79)	(5.93)	(9.78)

Means (Standard Deviations) for Target, Competitor, and Distractor items. No differences were found between conditions (*p*s > 0.1).

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