Learning and processing of orthography-to-phonology mappings in a third language

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Bilinguals' two languages are both active in parallel, and controlling co-activation is one of bilinguals' principle challenges. Trilingualism multiplies this challenge. To investigate how third language (L3) learners manage interference between languages, Spanish-English bilinguals were taught an artificial language that conflicted with English and Spanish letter-sound mappings. Interference from existing languages was higher for L3 words that were similar to L1 or L2 words, but this interference decreased over time. After mastering the L3, learners continued to experience competition from their other languages. Notably, spoken L3 words activated orthography in all three languages, causing participants to experience cross-linguistic orthographic competition in the absence of phonological overlap. Results indicate that L3 learners are able to control between-language interference from the L1 and L2. We conclude that while the transition from two languages to three presents additional challenges, bilinguals are able to successfully manage competition between languages in this new context.

Keywords: multilingualism, bilingualism, language learning, eye-tracking

Introduction

The majority of the world's population speaks more than one language (Grosjean & Li, 2013), often in communities where multiple languages are used frequently. Bilinguals' can communicate fluently in shifting linguistic environments because of their ability to control the relative activation of two languages, ensuring that only one intended language is used at any time. The ability to suppress one language while using another is particularly valuable while learning new languages, where a stronger entrenched language could otherwise out-compete a newly-acquired one. The language not currently in use cannot be completely suppressed, however, and it can still influence behavior during comprehension (Marian & Spivey, 2003b; Spivey & Marian, 1999) and production (Hoshino & Thierry, 2011; Jared & Kroll, 2001). Non-target activation may be particularly significant during language learning, because of the difference in experience with the new language relative to existing languages. To determine how multilinguals' prior language knowledge changes vocabulary learning and processing, in the current study we examined cross-linguistic interactions during third language learning.

The key challenge a language learner faces is how to rewire a fully functioning linguistic system to enable a new way of comprehending and expressing ideas. Because of the close link between language and thought, the learner may often need to suppress the much stronger existing language in order to give the new language a chance to compete. This skill of controlling language activation is one that bilinguals have spent a lifetime developing while navigating the world using two languages. To understand how third language learning is affected by bilingual experience, it is first necessary to identify the types of interactions that can occur across languages. For any pair of languages, their phonological, lexical, and grammatical features can be grouped into one of three categories: *Shared*, *Novel*, or *Conflicting*. Each of these categories may affect learning in different ways as discussed below.

Shared features overlap across languages. Cognates are one prominent example, words that share both form and meaning across languages, like the English-Spanish pair tiger/tigre. Shared features are an invaluable tool for language learners, who seek out cross-linguistic similarities whenever possible (Jarvis & Odlin, 2000; Ringbom & Jarvis, 2011). Furthermore, bilingual third language learners are able to flexibly transfer features from either of their existing languages based on perceived similarity between their L1/L2 and the L3 (Bartolotti & Marian, 2016a; Cenoz & Valencia, 1994; Murphy, 2003).

Novel features are absent in a learner's existing languages and must be acquired as a new structure. Many linguistic features (e.g., grammatical gender or lexical tone) are notoriously difficult for adults to acquire in a second language if they are not present in the native language (Ionin, Zubizarreta, & Maldonado, 2008; Parodi, Schwartz, & Clahsen, 2004; Thomas, 1989). Bilinguals, however, learn novel features better than monolinguals (Wang & Saffran, 2014), indicating that bilinguals' linguistic system can flexibly accommodate differences across languages.

Finally, *Conflicting* features involve the re-use of a similar structure across languages for different purposes, and are often a persistent source of errors (Bhela, 1999; Birdsong, 2014; MacWhinney, 2007). One large source of conflicting features at the onset of learning a new language is the correspondence between the letters of a language and its sounds. Acquisition of new vocabulary includes making associations between words' spellings and pronunciations, which utilizes letter-sound knowledge. Because world languages tend to change more rapidly in phonology than orthography, related languages tend to overlap more in their written than their spoken forms (Marian, Bartolotti, Chabal, & Shook, 2012). As a result, many of the same letters are used to represent sounds differently in two languages, causing difficulties for the language learner. An English speaker learning German must adapt to associate the letter W with the phoneme /v/ instead of the English sound /w/. These differences in letter use start to compound at the level of whole words. For example, the English-French false cognate *champ* (meaning *field* in French) is pronounced as /tʃæmp / in English and /ʃɑ̃/ in French. Bilinguals already have substantial experience managing competition between languages (Hoshino & Thierry, 2011; Jared & Kroll, 2001; Marian & Spivey, 2003a; Spivey & Marian, 1999), and depending on their specific pair of languages, will have more or less experience managing conflicting features between languages. Languages that are moderately related (e.g., English and Spanish) are likely to contain the greatest density of conflicting features, compared to closely related languages (e.g. German and Dutch) which contain more shared features, and distantly related language (e.g. English and Japanese) which contain mostly novel features to be learned.

Acquisition of new letter-sound correspondences is a good candidate for examining the effect of prior language knowledge on conflicting feature learning because of the close, bidirectional link between orthography and phonology in language processing. (Castles, Wilson, & Coltheart, 2011; Mayberry, del Giudice, & Lieberman, 2011; Salverda & Tanenhaus, 2010). The process by which bilinguals are able to learn novel correspondences between orthography and phonology, however, is still unclear. Frequently in natural language learning, letters in the new language correspond to non-native phonetic categories (e.g., for native English speakers, the French phoneme /y/ in *tu* and *sur* or the German phoneme /x/ in *ich* and *Buch*). Learning the phonology of another language thus often confounds acquisition of letter-sound mappings with learning new phonemes. Bilinguals are skilled at phonetic category learning (Bosch & Sebastián-Gallés, 2001) and at learning auditory words containing novel phonemes (Kaushanskaya & Marian, 2009b). To assess bilinguals' ability to acquire novel letter-sound mappings, then, it is necessary to control for phonetic learning ability.

In the current study, we isolated the ability to acquire letter-sound mappings by teaching Spanish-English bilinguals words in an artificial third language designed to recombine letters and sounds in novel ways. For example, the letter N corresponded to the phoneme /f/ in the novel language, and the word NAKE was pronounced /fuwɔ/. Because all orthographic and phonetic units were familiar to learners, we were able to isolate the effect of cross-language interference on acquisition of letter-sound mappings in a novel language. Our <u>first aim</u> was to determine how pre-existing knowledge of letter-sound mappings affects third language vocabulary learning in bilinguals. We predicted that each of bilinguals' existing languages would interfere with L3 learning, and that interference would decrease over time as familiarity with the new language increased. We also expected that individuals' vocabulary learning ability would be related to how well they acquired the L3's letter-sound mappings. Our second aim was to determine the degree to which bilinguals' other languages interfered with novel language processing after learning the new vocabulary. This was accomplished using an L3 spoken word processing task immediately post-training to take advantage of the diverging letter-sound correspondences between the L1/L2 and the L3. We expected orthographies of all three languages to activate during speech processing, leading to competition from L1 and L2 words that were orthographically similar to the spoken L3 word. Together, our two aims will reveal the mechanisms of language learning and control in emerging trilingualism.

Methods

Participants

Twenty Spanish-English bilinguals (16 females) participated after providing informed consent in accordance with the university's Institutional Review Board (IRB). Cognitive and linguistic profiles are summarized in Table 1. Language experience was obtained with the LEAP-Q (Marian, Blumenfeld, & Kaushanskaya, 2007); bilinguals learned both languages early in life (Spanish age of acquisition, *M* = 1.1 years, *SD* = 3.51; English age of acquisition, *M* = 2.95 years, *SD* = 2.92), were currently using each language frequently (Spanish *M* = 26.47% of the time, *SD* = 13.53; English *M* = 71.95%, *SD* = 14.92), and were highly proficient in each language (composite score of speaking, listening, and reading on a scale from 1-10: Spanish *M* = 8.40, SD = 1.03;

English M = 9.63, SD = 0.82).

Materials

Word learning

An artificial language, Colbertian (named after the comedian Stephen Colbert to engage participants in the task), was created using 13 letters and sounds present in English and Spanish (4 vowels and 9 consonants). Orthography-to-phonology mappings in Colbertian were designed to differ from both English and Spanish. For example, the letter N, corresponding to the phoneme /n/ in English and Spanish, instead represented the sound /f/ in Colbertian.

The thirteen-letter alphabet was used to create 24 disyllabic words, each composed of four letters. Colbertian words were designed to vary in their similarity to English and Spanish orthographic patterns. Novel words' orthographic neighborhood sizes (i.e., the number of English or Spanish words that differed by substitution, deletion, or addition of a single letter) and mean bigram probabilities (i.e., the average English and Spanish frequency of occurrence for each pair of letters) in English and Spanish were calculated using CLEARPOND (Marian, Bartolotti, Chabal, & Shook, 2012) and converted to z-scores for each language[1].

Because the novel words' English and Spanish bigram probabilities were highly correlated R^2 = .79, p < .001, we used English and Spanish neighborhood sizes (R^2 = .002, *n.s.*) to assess the independent influences of each language on Colbertian word learning. The 24 Colbertian words were divided into four groups (E+S+, E+S-, E-S+, and E-S-, where + and – refer to high and low neighborhood sizes respectively) using median splits of English and Spanish neighborhood size. Neighborhood size and mean bigram probabilities in each language are available in Table 2.

Auditory stimuli for all novel words were recorded by a monolingual English speaker with a neutral US-Midwestern accent.

Cross-linguistic competition

Twelve of the Colbertian words were created by substituting one letter of an English-Spanish cognate, yielding a word with a cross-linguistic orthographic competitor in each language that did not overlap phonologically. For example, the cognate *rose-rosa*, pronounced /ɹoʊz / - /rosa/, only overlaps orthographically with the Colbertian word ROKE, pronounced /hiwɔ/. The remaining twelve Colbertian words were created by substituting one letter of an English non-cognate word, yielding a single-language orthographic competitor with no phonological overlap. For example, the noncognate *cake*, meaning *tarta* in Spanish, and pronounced /keɪk/ - /tarta/, overlaps in English with the Colbertian word NAKE, pronounced /fuwɔ/. Colbertian words in the cognate and noncognate conditions were matched on the following (see Table 3): English and Spanish mean bigram probabilities using CLEARPOND (Marian et al., 2012), English and Spanish neighborhood sizes using CLEARPOND (Marian et al., 2012), number of letters, and in the number of English-only phonemes they contained (all *p*s > .05). In addition, Colbertian words were matched in the number of letters they overlapped with the English cognate and noncognate competitors, *p* > .9 (Spanish competitors of course only overlapped with the Colbertian target in the cognate list), and never overlapped with competitors phonologically. Cognates overlapped with the target 42% of the time at the onset and 58% of the time at the offset; Noncognates were split 50% onset overlap and 50% offset overlap.

This design allowed us to isolate the effect of orthography in one or two known languages on L3 phonological processing. A Colbertian word (target), its cognate or noncognate neighbor (orthographic competitor) and two non-overlapping filler words comprised a single test set; black and white line drawings were selected to pair with each word in a set for use in a visual world search task. Pictures were highly recognizable, with naming consistency in both English and Spanish above 80% in either the International Picture Naming database (E. Bates et al., 2003) or production norms ($N = 20$) collected using Amazon's Mechanical Turk (https://www.mturk.com). Picture names were matched across the three picture types (target, competitor, filler) and across cognate/noncognate conditions within each picture type on the following measures in both English and Spanish: neighborhood size using CLEARPOND (Marian et al., 2012), mean bigram probabilities using CLEARPOND (Marian et al., 2012) lexical frequency using SUBTLEX-US and SUBTLEX-ESP (Brysbaert & New, 2009; Cuetos, Glez-Nosti, Barbón, & Brysbaert, 2011), concreteness/imageability/familiarity using the MRC Psycholinguistic database (Coltheart, 1981), and number of letters (all ps > .05).

Procedure

Participants completed five tasks in order in a single session. First, in *word learning: orthography*, they learned to match the written and spoken forms of each Colbertian word. Second, in *word learning: meaning*, they learned to associate the Colbertian words with pictures. Third, in *cross-linguistic competition*, participants completed a visual world search task to assess activation of orthography across languages during spoken word processing in a third language. Fourth, in *word learning: letter knowledge*, participants matched new, untrained spoken Colbertian words to their spellings by utilizing their knowledge of Colbertian's letter-sound mappings. Finally, participants completed the *cognitive & linguistic battery*, including standardized tests of non-verbal IQ and phonological memory as well as a bilingual language experience questionnaire. Stimuli presentation was controlled by the experimental software MATLAB with the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997).

Eye movements in the visual world task were recorded with an SR Eyelink 1000 eyetracker at 1000 Hz.

(1) Word learning: Orthography

First, participants were exposed to the 24 Colbertian words, one at a time. A single word was presented auditorily over headphones while its spelling was presented in the center of the computer screen; participants repeated the word out loud and clicked the mouse to advance. Then participants completed individualized training regimes to learn the language (Figure 1A). A single training block included 24 trials with each word as a target once. In each trial, participants viewed four written words on the screen and heard the target over headphones. After making a selection by clicking on one of the written words, accuracy was recorded and the correct answer was provided as feedback so that participants could improve over time. Additional training blocks were repeated until the participant achieved a performance criterion of 90% accuracy on two consecutive blocks.

(2) Word learning: Meaning

After learning the spellings of the auditory words, participants learned to associate the words they had just acquired with picture meanings. First, participants were shown all 24 pairings. A Colbertian word was presented visually and auditorily along with four pictures, and the matching picture was indicated by a red box. Then, as in word-form learning, participants completed individualized training regimes to master the pairings (Figure 1B) using the same performance criterion (90% accuracy on two consecutive testing blocks). In each trial, the Colbertian target word was presented visually and auditorily, and four pictures were shown in the corners of the screen (in order to reduce novelty effects in the subsequent cross-linguistic competition task, competitors and fillers were used as foils during learning, but were paired with different targets). After selecting a picture, the correct answer was provided as feedback so that participants could reinforce the correct association.

(3) Cross-linguistic competition

The visual world search task used eyetracking to assess simultaneous activation of both Colbertian orthography and English/Spanish orthography during spoken word processing in the newly-learned L3. In each trial, participants first viewed a fixation cross for 1000 ms to orient their gaze to the center of the screen. Then four pictures were presented in the corners of the screen, and after a 500 ms delay, the Colbertian target was played over headphones; the orthographic form of the target was never shown in the task (Figure 2). Participants clicked the matching image as quickly and accurately as possible (no feedback was provided). In 12 Non-cognate Competitor trials, the English (but not Spanish) orthographic form of a competitor picture in the display overlapped with the orthographic form of the Colbertian target word (e.g., English competitor CAKE/TORTA for the target /fuwɔ/, spelled NAKE). In 12 Cognate Competitor trials, both the English and Spanish orthographic forms of one competitor picture in the display overlapped with the Colbertian target's spelling (e.g., cognate competitor ROSE/ROSA for the target /hiwɔ/, spelled ROKE). Note that competitors never overlapped phonologically with the target in either language, allowing us to isolate the effect of orthographic overlap on spoken word processing. The 12 Non-cognate Competitor trials and 12 Cognate Competitor trials were intermixed with 24 Filler trials used to mask the experimental manipulation, in which no pictures' names overlapped orthographically or phonologically with the target in either language.

(4) Word learning: Letter knowledge

Participants' acquisition of Colbertian's underlying letter-to-sound mappings was assessed using a novel-word generalization task. In each trial, four new, untrained Colbertian written words were presented in the four corners of the screen and the novel word's auditory form was presented over headphones. The participant selected the matching word, and no feedback was provided. In 24 Low Similarity trials, knowledge of a single letter was sufficient to identify the target, because all four words contained unique letters at each position. (e.g., Target /suzɔ/ spelled BAPE does not have any letters in the same position as Foils KOVI, VEDO, or RINA). In 24 High Similarity trials, each foil partially overlapped with the target, and thus an accurate response required knowledge of multiple Colbertian letters (e.g., Target /wɔtʃæ/ spelled KEDI shares letters with foils **K**OVA, NA**D**O, and B**E**R**I**). Low and High Similarity trials were intermixed during testing.

(5) Cognitive & linguistic battery

The experiment concluded with three assessments: (1) Non-verbal IQ was measured using the block design and matrix reasoning subtests of the *Wechsler Abbreviated Scale of Intelligence* (PsychCorp, 1999); (2) Phonological memory was measured using the digit span and nonword repetition subtests of the *Comprehensive Test of Phonological Processing* (Wagner, Torgesen, & Rashotte, 1999); and (3) bilingual language history and experience was measured using the *Language Experience and Proficiency Questionnaire* (Marian et al., 2007).

Data Analysis

Word learning

Participants' learning data were normalized for duration (i.e., number of blocks) in order to compare the shape of learning trajectories over time. Time normalization involved linear interpolation to resample accuracy at 51 evenly spaced intervals (from 0 to 100% in 2% increments) on each participant's learning curve. Each wordlikeness condition was normalized separately. Change in accuracy over time in orthographic word learning was analyzed using growth curve analysis (Mirman, Dixon, & Magnuson, 2008; Mirman, Magnuson, Graf Estes, & Dixon, 2008), a technique specifically designed to assess change over time, with the lme4 package (D. M. Bates, Machler, Bolker, & Walker, 2014) in R (R Core Team, 2016). Growth curve analysis is a form of multilevel regression that simultaneously estimates the effects of individuals and of experimental manipulations on timecourse data. A base second-order orthogonal polynomial captured the curvilinear shape of learning gains over time. Each of the polynomial terms in the base model was then estimated in a level-2 model that assessed the effects of word-level factors (English or Spanish wordlikeness) or participant-level factors (cognitive profile, word generalization skill). In these models, an effect on the intercept term corresponds to changes in the average height of the curve across the analysis window. The linear term reflects the overall slope of the learning curve, the quadratic captures symmetric effects around the centerline of the curve, and the cubic captures asymmetric effects around the center.

The full model included all time terms and random effects of participant on all time terms, as well as fixed effects of English wordlikeness and Spanish wordlikeness plus their interaction on all time terms. Additional models were created that added participants' IQ, phonological memory capacity, or performance on the "Colbertian

Word learning: letter knowledge" task to all time terms. Significance of fixed effects was assessed using the Satterthwaite approximation for degrees of freedom and type III sum of squares in the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2016).

Cross-linguistic competition

Eyetracking fixations were also analyzed using growth curve analysis. Visual fixations were analyzed from auditory word onset until the point at which fixations to the target peaked, indicating final target selection (i.e., 850ms post-word onset in the Non-cognate Competitor condition, and 800ms post-word onset in the Cognate Competitor condition). Within this window, a base fourth-order orthogonal polynomial was used to capture the rise and fall of visual fixations to the visual competitor and to the average of both filler objects in the display, with random effects of participant and participant-by-condition for each time term. Additional models added a fixed effect of condition (Competitor vs Filler) to each time variable in turn, and the change in model fit was assessed as in the learning task using a Chi-square test. The effects of participants' cognitive factors and word generalization skill were assessed by separately adding each variable to the full model including interaction terms with condition. The effects of words' lexical characteristics were assessed in a similar way using a separate model including item-averaged data and random effects of items.

Results

Word learning

Bilinguals achieved the 90% accuracy criterion in the *word learning: orthography* task after an average of thirteen blocks (*M* = 12.70, *SD* = 7.32, *Range* [5, 34]), and in the *word learning: meaning* task after three blocks (*M* = 2.75, *SD* = 0.64, *Range* [2, 4]). Training was designed to equate knowledge of the trained words across participants by varying the length of training, and accordingly, accuracy in the subsequent *cross-linguistic competition* task was high, M = 99.0%, SD = 2.3%, Range [91.7, 100].

Orthographic word learning was analyzed after normalizing time across participants, and examined the independent effects of English and Spanish similarity on Colbertian word learning (Figure 3, Table 4). English similarity had significant effects on the intercept, linear, quadratic, and cubic terms. Spanish similarity had significant effects on the linear, quadratic, and cubic terms. English and Spanish similarity interacted on the intercept, linear, quadratic, and cubic terms. Colbertian words that had low similarity to both languages (E-S-, gray) had the highest accuracy at the beginning of training, but the slowest rate of improvement with additional training. Englishlike words (E+S-, blue) and Spanishlike words (E-S+, red) displayed similar patterns to each other, characterized by rapid improvement early in training. The dual English and Spanishlike words (E+S+, purple) had the slowest improvement rate.

After learning whole words, participants demonstrated partially successful extraction of Colbertian's individual letter-sound correspondences based on their accuracy in the *word learning: letter knowledge* task. Participants identified the correct orthographic form for novel auditory words according to Colbertian rules 83.10% of the time in the Low-similarity condition (*SD* = 22.57, *Range* = [20.83, 100.00]). In the High-similarity condition, which required more extensive letter-sound knowledge, accuracy dropped to 74.31% (*SD* = 26.17, *Range* = [29.17, 100.00], $t(17) = 2.74$, $p < .05$, 95% CI = [2.02, 15.57], $d = 0.36$).

We observed a close relationship between individuals' knowledge of Colbertian letter-sound mappings and performance on the orthographic word learning task. Letter knowledge in the Low- or High-similarity conditions had the same effects on word learning, and thus an average letter knowledge score was used in the final analysis

(Table 5). Letter knowledge had significant effects on the intercept and linear terms; higher letter knowledge scores were associated with increased curve height and decreased learning rate (due to the effect of reaching ceiling performance). These results suggest that individuals who learned more whole words as training began were also those who were able to learn and retain more individual letter-sound mappings.

Cross-linguistic competition

The visual world search task assessed activation of multiple orthographies during auditory word processing in the L3. Fixations to the target, competitor, and filler pictures began to diverge at word onset; analysis was restricted to a window from word onset to the point of peak target fixation (850ms post-word onset for the non-cognate condition and 800ms post-word onset for the cognate condition), an indicator of target selection (Figure 4). The proportion of fixations to orthographic competitors was compared to fillers using growth curve analysis.

In the non-cognate condition, only the English label for the pictured object overlapped orthographically with the target (e.g., Colbertian target /fuwɔ/, spelled NAKE and English competitor *cake*, Spanish *tarta*). The base fourth-order polynomial time model of visual fixations was significantly improved by adding an effect of Competitor ($\Delta LL = 5.53$, $X^2(5) = 11.07$, $p < .05$). The Competitor had a significant effect on the linear term ($Estimate = -0.128$, $SE = 0.039$, $z = 3.28$, $p < .01$), which captured the steep drop in fixations to non-cognate competitors over the analysis window following the high early fixation peak (Figure 5). These results suggest that the L3 auditory word immediately activated its matching L3 orthographic form, which then initially spread activation to words in the non-target language, English. The swift decrease in competitor fixations may reflect the influence of an inhibitory process to suppress activation of non-target language competitors.

In the cognate condition, both the English and the Spanish labels for the pictured object overlapped orthographically with the target (e.g., Colbertian target /hiwɔ/, spelled ROKE, overlaps with the English/Spanish cognate *rose/rosa*). The base fourth-order polynomial time model of visual fixations was also significantly improved by adding an effect of Competitor (ΔLL = 7.56, $X^2(5) = 15.12$, $p < .01$). In contrast to the non-cognate display condition, however, in the cognate condition, the Competitor had significant effects on both the linear (*Estimate* = 0.096, *SE* = 0.037, $z = 2.612$, $p < .01$) and the quadratic terms (*Estimate* = -0.073, *SE* = 0.032, $z = 2.274$, $p < .05$). These two effects capture 1) a monotonic decrease in filler fixations over the window absent from competitor fixations, and 2) a peaked rise and fall of fixations to the competitor in the middle of the window (Figure 6), representing a delayed activation peak relative to the non-cognate competitors. This pattern of results is consistent with lower baseline levels of activation for the L1-L2 cognates due to accumulated inhibition of both the L1 and L2 during L3 processing.

Model fits were not improved by adding participant factors (IQ, phonological working memory, or word generalization skill) or item factors (wordlikeness, overlap position and amount, frequency, concreteness, imageability, familiarity), *p*s > .05.

Discussion

The current study examined how trilinguals learn to control competition between multiple pairs of languages. We taught bilinguals an L3 containing features that conflicted with their L1 and L2. Specifically, Spanish-English bilinguals learned 24 words in an artificial language with letter-sound mappings that mismatched English and Spanish (e.g., the novel word NAKE was pronounced /fuwɔ/). Our first aim was to determine how alphabetic knowledge in two languages affects the onset of L3 learning, and we found differences in word learning rate depending on similarity to English and/or Spanish. Specifically, increased similarity to existing languages decreased word learning at the start of training, due to greater cross-linguistic interference (with more interference for words that overlapped with two languages compared to one), and this interference was reduced with additional training. Our second aim was to compare *orthographic* interference from one or both prior languages during *auditory* L3 processing. We found evidence for activation of orthography in all three languages in response to spoken L3 words. Specifically, participants fixated pictures of L1/L2 orthographic competitors more than unrelated pictures, in the absence of phonological overlap. Additionally, cognates, which competed with the L3 in each language, had a delayed time of activation compared to non-cognates, due to additive suppression of each language. Overall, results demonstrate how L3 learners adjust the way that competition is managed during the transition from bilingualism to trilingualism.

Word learning

We found that words in the novel language were learned at different rates depending on their similarity to English and Spanish lexical patterns. Wordlikeness in the current study was calculated based on novel words' orthographic neighborhood sizes in English and Spanish, yielding four classes of words: Unwordlike, Englishlike, Spanishlike, and English-Spanishlike (the words' bigram probabilities in English and Spanish were highly correlated and thus did not distinguish between language-specific effects). For auditory words, phonological neighborhood size and phonotactic probabilities have both been found to affect novel word learning (Roodenrys & Hinton, 2002; Storkel, Armbrüster, & Hogan, 2006; Thorn & Frankish, 2005), and orthographic neighborhood size and orthotactic probabilities have been shown to affect written learning in monolinguals (Bartolotti & Marian, 2016b) and bilinguals (Bartolotti & Marian, 2016a). Typically, high wordlikeness confers a learning benefit due to overlap with existing structures. Here, we observed a rate advantage for similarity to either or both languages, all of which were learned faster than unwordlike items as training progressed. However, this rate effect was coupled with lower wordlike accuracy in the earliest blocks, reflecting an initial wordlike *disadvantage*. Written novel words in isolation trigger automatic generation of an appropriate phonological form (Johnston, McKague, & Pratt, 2004), and this process in bilinguals can be guided by sublexical cues to language membership (Oganian, Conrad, Aryani, Heekeren, & Spalek, 2015). It is possible that the novel words with more Englishlike or Spanishlike forms more strongly evoked nontarget phonological representations, hindering acquisition of the correct form in the novel language. In support of this interpretation, novel words that were similar to both English and Spanish showed a pattern of greater interference than words that resembled only one language, suggesting that activation of phonological representations in both English and Spanish had a greater cost. With additional training, participants were able to overcome this initial interference, and even to derive a benefit from the novel words' more familiar written forms. In contrast, monolinguals in a similar language learning context consistently experience a wordlike disadvantage throughout training (Bartolotti, 2015). This pattern observed in bilinguals is consistent with observed bilingual benefits during third language learning compared to monolingual second language learning (Cenoz, 2003; Kaushanskaya & Marian, 2009a; Sanz, 2000).

Although the training was designed to equate participants' knowledge of the trained Colbertian vocabulary, there were individual differences in how well participants learned the underlying structure of the novel language. The ability to match untrained written and spoken Colbertian words in the generalization task depends on knowledge of individual letter-sound correspondences, and there was wide variability in performance on the task across participants. If we take generalization accuracy as a marker of Colbertian letter knowledge, we see that increased letter knowledge was associated with accelerated word learning during the training task. At no point in training were participants told to attend to individual letters, and they did not know that they would later be asked to generalize to new words. Instead, letter knowledge was an emergent property of whole word instruction, to a varying degree across individual learners

Other cognitive factors, including nonverbal IQ and phonological memory, were not related to differences in learning across individuals. Fluid intelligence has been shown to be associated with some language learning tasks (Brooks, Kempe, & Sionov, 2006). However, because the artificial language was designed to isolate acquisition of new mappings between orthography and phonology, without the confound of learning new letters or phonemes, cognitive demands may have been lower, making the task less sensitive to differences in cognitive ability. Phonological memory plays an important role in repetition and production of unfamiliar sequences (Bartolotti & Marian, 2014; Gathercole, 2006; Gupta, 2003), but may not have been a significant predictor of success in the current study due to the lower memory demands on individual trials. Both the auditory and the written forms of the novel words were presented simultaneously during testing, requiring only knowledge of the correct association between the two. As a result, memory demands for the word forms themselves was minimized.

Cross-linguistic competition

Remarkably, we found that spoken L3 words increased activation of similarly-spelled L1 and L2 words, despite complete lack of phonological overlap; this provides support for multi-step cascading activation in the trilingual language system. Specifically, 1) L3 phonology activates L3 orthography (e.g., the phonemes in /fuwɔ/ activate the letters in *nake*), 2) L3 orthography co-activates L1 and L2 orthographic neighbors (e.g., *nake* activates the English word *cake*), and 3) L1 and L2 orthographic neighbors activate corresponding L1 and L2 lexical items that compete for selection with the L3 target (e.g., the image of the cake draws eye movements). These findings from emerging trilinguals are consistent with recent work that provides evidence for cascading activation in bilinguals (Shook & Marian, 2017) – i.e., a Spanish-English bilingual activates *shovel* when they hear *duck*, because *duck* and *shovel* are phonologically related in Spanish (*pato* and *pala*, respectively). Our study provides evidence for cascading activation in trilinguals both across modalities (phonology to orthography) and across languages (L3 to L1 and L2), supporting a highly interactive account of the trilingual language system.

Notably, we observed cross-linguistic interference from the L1 and L2 into the L3 immediately after L3 learning. It remains an open question whether new L3 words would similarly impact L1 and L2 processing, as interference from L3 may require L3 lexical consolidation over a longer time scale (see Dumay & Gaskell, 2007; Tamminen & Gaskell, 2008).

We were able to gain further insight into patterns of parallel language activation and interference during language learning by comparing L3 processing of L1-L2 cognates and non-cognates. Cross-language competitors were designed to either overlap with the novel written word in English alone (target *nake* overlaps in English with the non-cognate *cake-tarta*) or in both English and Spanish (target *roke* overlaps in both English and Spanish with the cognate *rose-rosa*). We observed a later fixation peak for cognate competitors compared to non-cognates. This curious finding, where conceivably *more* competition from cognates nevertheless results in a *delayed* competition effect, may be explained by accounting for inhibition of multiple languages. Linck, Schweiter, and Sunderman (2009) propose extending Green's

Inhibitory Control model (Green, 1998) to trilinguals using language-specific inhibition for each language. Under this model, both the L1 and L2 would be independently inhibited during L3 processing. Because cognates share overlapping forms across languages, the effect of L1 and L2 suppression may decrease the baseline activation of cognates' overlapping form more than noncognates' separate forms in each language. This pattern of differences in baseline activation would be consistent with our observed delayed peak for cognates, which have to overcome greater baseline inhibition.

Alternatively, the delayed cognate effect may be caused by the ambiguity in linguistic input. As speech is processed, competing lexical items become activated, and because activated cognates are consistent with multiple languages, the input parser may delay selection to account for possible language shifts. The delayed cognate peak we observed may thus be evidence of a more flexible language system, which keeps the lexical selection window open for an extended period when activated items are consistent with multiple languages.

Our findings suggest that bilingual language learners can rapidly integrate a third language into their linguistic system to a degree sufficient for interactive activation across languages and modalities. It is well established that spoken words in one language generate activation of phonological competitors in other known languages (Blumenfeld & Marian, 2007; Chambers & Cooke, 2009; Marian & Spivey, 2003b; Spivey & Marian, 1999), but the process by which activation occurs is debated (see Costa, Pannunzi, Deco, & Pickering, 2016). Notably, spreading activation can occur in bilinguals even when there is no feature overlap, as in bilingual users of a spoken and a sign language (Giezen, Blumenfeld, Shook, Marian, & Emmorey, 2015; Shook & Marian, 2012), and even during a completely non-linguistic task (Chabal & Marian, 2015). In the absence of bottom-up pathways in these types of tasks, activation of competitor items can occur through excitatory top-down or lateral connections between lexical entries at different levels of processing (Shook & Marian, 2013), or through strengthened associations resulting from a history of co-activation.

In fact, it has been suggested that activation of words in a non-target language may be explained solely by associations developed gradually over the course of learning a second language, and not due to parallel language activation (Costa et al., 2016). However, this mechanism is unable to account for the pattern of results observed in the current study. When participants fixated a *cake* upon hearing /fuwɔ/, this could not have occurred as a result of learned associations, because cake and the target word had never been seen or heard together by participants. The auditory signal itself shared no overlap with the phonological form of the target, /keIk/, and thus there could be no bottom-up activation of the orthographic competitor in response to the input. Instead, activation of the learned orthographic form *nake* for the novel word /fuwɔ/ spreads to similarly spelled items in the non-target languages, including the English orthographic neighbor *cake*. This finding provides strong evidence for parallel language activation in multilinguals during spoken word comprehension, as the results we observe can only be accounted for by online activation of cross-linguistic competitors as lexical input unfolds.

For bilinguals, the problem of language control in most contexts can be managed with an inverse relationship: when one language is needed and should remain active, the other should be deactivated. This kind of simple relationship, however, is itself insufficient to handle the complexities of language control in trilinguals. With additional languages comes the need to selectively increase activation of a single language, and accordingly, trilinguals have been found to outperform bilinguals in tasks requiring inhibitory control (Hsu, 2014). The process by which trilinguals' language control develops over time remains an important area of study.

Conclusion

Uncovering the early stages of third language learning provides critical insight into how trilinguals' three languages mutually interact. Our results demonstrate that emerging trilinguals experience cross-linguistic influences from both of their existing languages while learning and processing a newly-learned language. Experience controlling activation of an L1 and L2 enables third language learners to overcome between-language interference while acquiring conflicting features in the new language. Notably, we also show that during spoken word processing, all three orthographies in trilinguals' three languages become activated. The interactivity that occurs across languages and across modalities increases non-linearly in multilinguals with the number of languages known, and multilinguals' ability to successfully manage these interactions for seamless language processing is a testament to the innate flexibility of the human linguistic system.

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Footnotes

1 The novel words had larger English (M = 11.33, SE = 1.33) than Spanish (M = 4.58, SE = 0.54) neighborhood sizes, but note that English words on average have larger neighborhoods than Spanish words (Marian et al., 2012). The novel words' English neighborhood size was comparable to four-letter English words' average size of 10.33, $t(23) = 0.75$, *n.s.* Spanish neighborhood size was slightly smaller than four-letter Spanish words' average size of 7.87, $t(23) = 6.03$, $p < .001$.

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Table 1. Participant linguistic and cognitive backgrounds.

Measure	Mean (SD) [Range]	
Age (years)	22.25 (2.99) [18.42-28.58]	
Nonverbal Intelligence[1]	108.3 (11.93) [89-134]	
Phonological Memory[2]	106.9 (12.69) [79-124]	
	English	Spanish
Speaking Proficiency[3]	9.63 (0.83) [7-10]	8.32 (1.38) [6-10]
Listening Proficiency[3]	9.63 (0.83) [7-10]	9.11 (0.94) [7-10]
Reading Proficiency[3]	9.63 (0.83) [7-10]	7.74 (1.41) [5-10]
Composite Proficiency[3]	9.63 (0.82) [7.33-10]	8.40 (1.03) [6.33-10]
Age of Acquisition (years)[3]	2.95 (2.91) [0-9]	1.11 (3.51) [0-14]
Current Usage (%)[3]	71.95 (14.92) [45-97]	26.47 (13.53) [3-50]

Note: 1-Performance IQ standard score, *Wechsler Abbreviated Scale of Intelligence* (*WASI*; PsychCorp, 1999); 2-Standard score, *Comprehensive Test of Phonological Processing* (*CTOPP*; Wagner, Torgesen, & Rashotte, 1999); 3-*Language Experience and Proficiency Questionnaire* (*LEAP-Q*; Marian, Blumenfeld, and Kaushanskaya, 2007), self-rated proficiency is rated on a scale of 1-10.

Table 2. Novel word lexical properties by condition

Condition	Neighborhood size		Bigram probability	
	English	Spanish	English	Spanish
E+S+	17.50	6.75	0.0105	0.0113
E+S-	16.63	3.00	0.0070	0.0051
E-S+	6.57	6.57	0.0064	0.0070
E-S-	4.60	2.60	0.0046	0.0044

Table 3. Stimuli lexical characteristics

	Condition					
Measure	Noncognate	*SE*	Cognate	*SE*	*t*	*p*
Colbertian Target						
EN Bigram	.0065	.0008	.0073	.0011	$t(20.2) = 0.56$	.58
EN Neighborhood	11.17	1.39	11.5	2.34	$t(17.9) = 0.12$	.90
SP Bigram	.0064	.0013	.0067	.0014	$t(21.7) = 0.12$	.90
SP Neighborhood	4.5	0.93	4.67	0.61	$t(18.9) = 0.15$	.88
Length (letters)	4	0	4	0	-	-
English-only phonemes	2	0.37	1.75	0.18	$t(15.9) = 0.61$	.55
Competitor (English)						
Bigram	.0087	.0009	.0091	.0016	$t(16.8) = 0.20$	.84
Neighborhood	13.42	1.64	10.17	3.33	$t(16.0) = 0.88$	.39
Length (letters)	4.25	0.18	5	0.56	$t(13.2) = 1.27$	.23
Colbertian letter overlap	2.58	0.15	2.58	0.14	$t(22) = 0$	1.00
Colbertian phone overlap	0	0	0	0	-	-
Frequency (zipf)	4.058	0.139	4.069	0.146	$t(21.9) = 0.05$	.96
Competitor (Spanish)						
Bigram	.0101	.0012	.0095	.0025	$t(16.0) = 0.23$	.82
Neighborhood	5	1.39	6.33	1.65	$t(21.4) = 0.62$	.54
Length (letters)	5.58	0.34	5.25	0.52	$t(18.7) = 0.54$	.60
Colbertian letter overlap	0.17	0.11	2.33	0.14	$t(20.9) = 11.96$	.00
Colbertian phone overlap	0	0	0	0	-	-
Frequency (zipf)	3.892	0.134	4.059	0.157	$t(21.4) = 0.81$	.43

Note: EN = English, SP = Spanish, Bigram = mean bigram probability, Neighborhood = orthographic neighborhood size, SE = standard error. *t*-tests used the Satterthwaite approximation for degrees of freedom.

Table 4. Growth curve analysis of English/Spanish similarity on Colbertian word learning.

Fixed Effect	Estimate	SE	df	t	p
(Intercept)	71.43	2.26	20	31.64	<.001***
Linear	118.97	8.78	20	13.55	<.001***
Quadratic	-13.64	4.99	20	-2.73	0.013*
Cubic	0.88	4.77	20	0.19	0.855
Eng	-1.87	0.43	4000	-4.40	<.001***
Spa	-0.50	0.43	4000	-1.18	0.238
Eng:Linear	11.75	3.04	4000	3.87	<.001***
Eng:Quad	-9.60	3.04	4000	-3.16	0.002**
Eng:Cubic	-8.64	3.04	4000	-2.84	0.004**
Spa:Linear	13.77	3.04	4000	4.53	<.001***
Spa:Quad	-11.30	3.04	4000	-3.72	<.001***
Spa:Cubic	-6.66	3.04	4000	-2.19	0.028*
Eng:Spa	-7.97	0.85	4000	-9.36	<.001***
Eng:Spa:Linear	21.13	6.08	4000	3.48	<.001***
Eng:Spa:Quad	32.95	6.08	4000	5.42	<.001***
Eng:Spa:Cubic	-21.65	6.08	4000	-3.56	<.001***

Note: Eng = English wordlikeness, Spa = Spanish wordlikeness. Contrasts were centered, and *t*-tests used the Satterthwaite approximation for degrees of freedom * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 5. Growth curve analysis of Letter Knowledge and English/Spanish similarity on Colbertian word learning.

Fixed Effect	Estimate	SE	df	t	p
(Intercept)	49.27	7.15	18	6.89	<.001***
Linear	182.20	30.66	18	5.94	<.001***
Quadratic	-6.46	18.71	18	-0.35	0.734
Cubic	-7.83	16.01	18	-0.49	0.631
Eng	-1.83	0.45	3618	-4.10	<.001***
Eng:Linear	12.40	3.19	3618	3.89	<.001***
Eng:Quad	-8.87	3.19	3618	-2.78	0.005**
Eng:Cubic	-9.38	3.19	3618	-2.94	0.003**
Spa	-0.41	0.45	3618	-0.93	0.353
Spa:Linear	13.37	3.19	3618	4.19	<.001***
Spa:Quad	-8.48	3.19	3618	-2.66	0.008**
Spa:Cubic	-8.41	3.19	3618	-2.64	0.008**
Eng:Spa	-7.24	0.89	3618	-8.11	<.001***
Eng:Spa:Linear	15.37	6.38	3618	2.41	0.016*
Eng:Spa:Quad	30.20	6.38	3618	4.74	<.001***
Eng:Spa:Cubic	-18.81	6.38	3618	-2.95	0.003**
Letter	0.28	0.09	18	3.25	0.004**
Letter:Linear	-0.80	0.37	18	-2.13	0.047*
Letter:Quad	-0.06	0.23	18	-0.28	0.784
Letter:Cubic	0.08	0.20	18	0.41	0.683

Note: Eng = English wordlikeness, Spa = Spanish wordlikeness, Letter = Letter Knowledge (word generalization task). Contrasts were centered, and *t*-tests used the Satterthwaite approximation for degrees of freedom * $p < .05$, ** $p < .01$, *** $p < .001$.

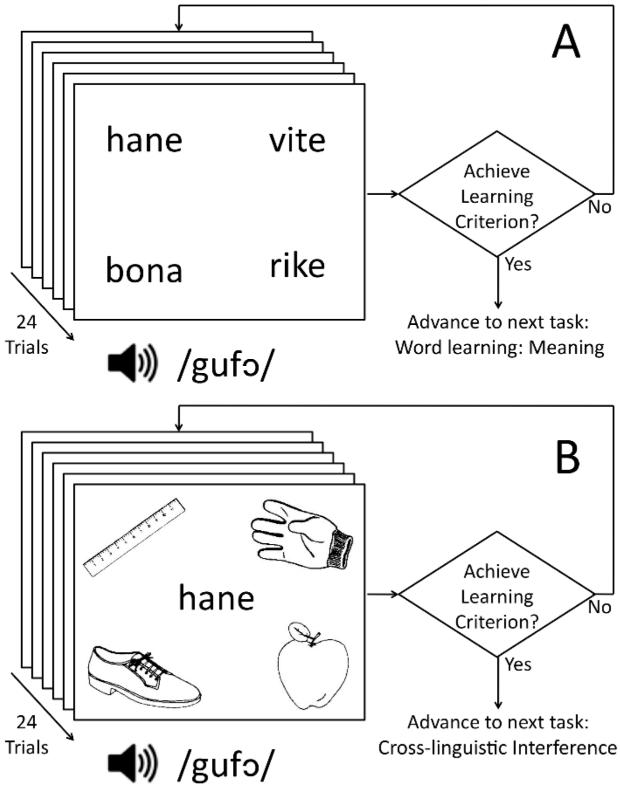

Figure 1. Word learning procedure. A) During orthographic word learning, participants heard a target word in the new language and selected its matching written form. Feedback was provided after each trial to reinforce the correct association. Participants repeated blocks of 24 trials until they achieved a learning criterion of 90% accuracy on two consecutive blocks. B) During word-meaning learning, participants heard and saw a Colbertian target and selected the matching picture. Corrective feedback was provided. As in orthographic word learning, training continued until the performance criterion of 90% accuracy on two consecutive blocks was achieved.

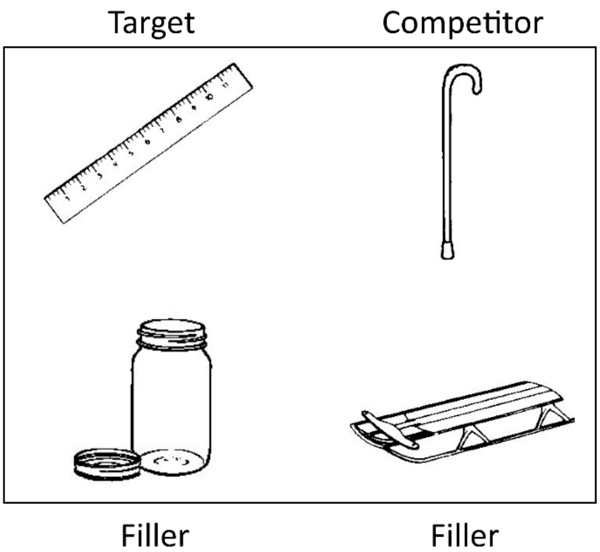

Figure 2. Cross-linguistic orthographic competition. In each trial, participants viewed four pictures and heard an auditory Colbertian word (e.g., /gufɔ/, spelled HANE, meaning *ruler*) that referred to the target. The English name of a competitor picture in the display was an orthographic, but not phonological, neighbor of the Colbertian target (e.g., CANE, /keɪn/). Filler items did not overlap with any other picture orthographically or phonologically.

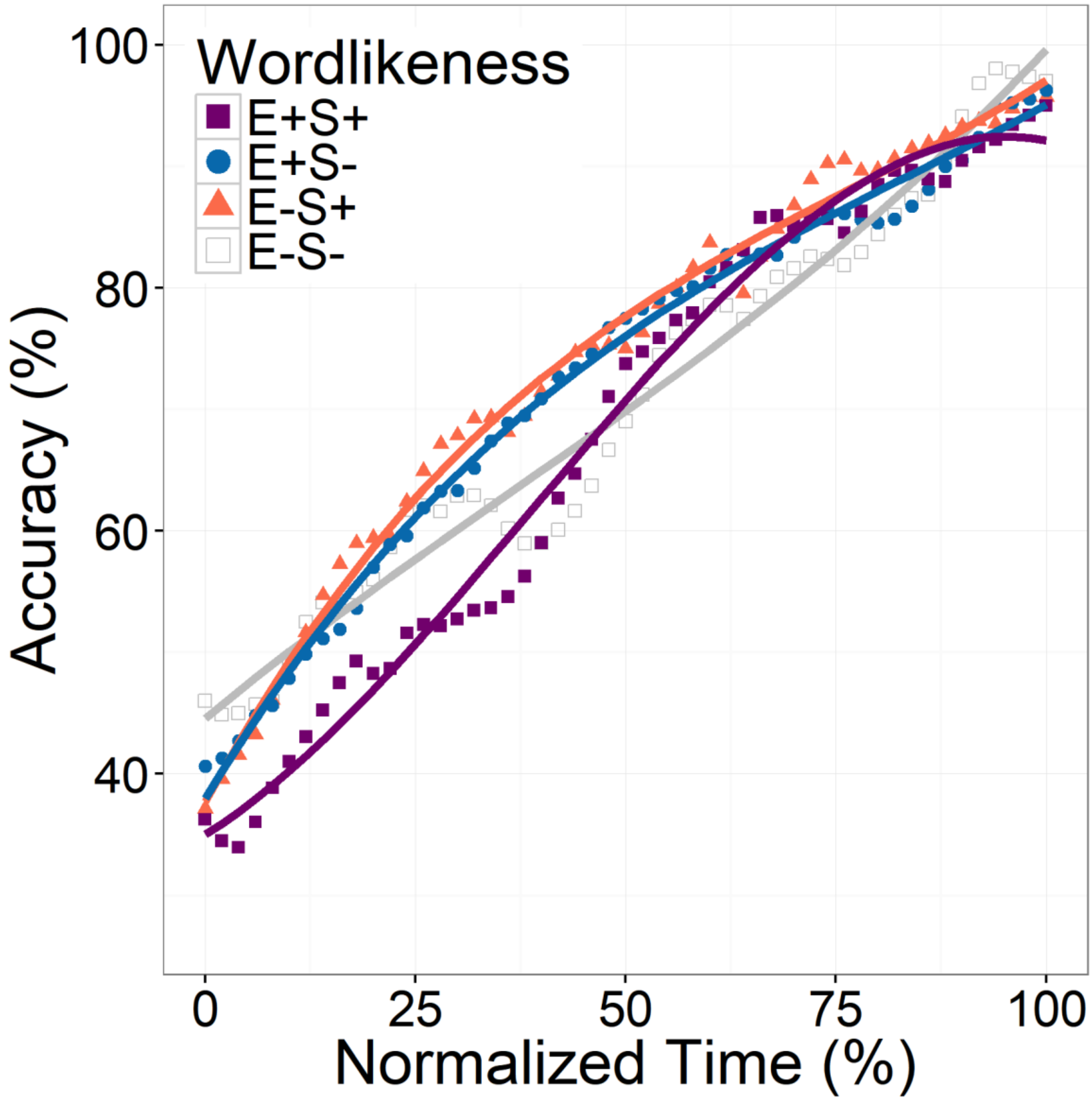

Figure 3. Wordlikeness and Orthographic-word learning. New words that had low similarity to both English and Spanish (E-S-, gray) were identified most accurately at first, but progressed at the slowest rate with additional training. Words that resembled either English (E+S-, blue) or Spanish (E-S+, red) improved the fastest with training after an initial disadvantage. Similarity to both languages (E+S+, purple) recovered more slowly from an initial disadvantage. Results indicate interference from known letter-sound mappings that scales with the number of overlapping languages, and that interference can be overcome with sufficient training. Learning curves were normalized for duration across participants.

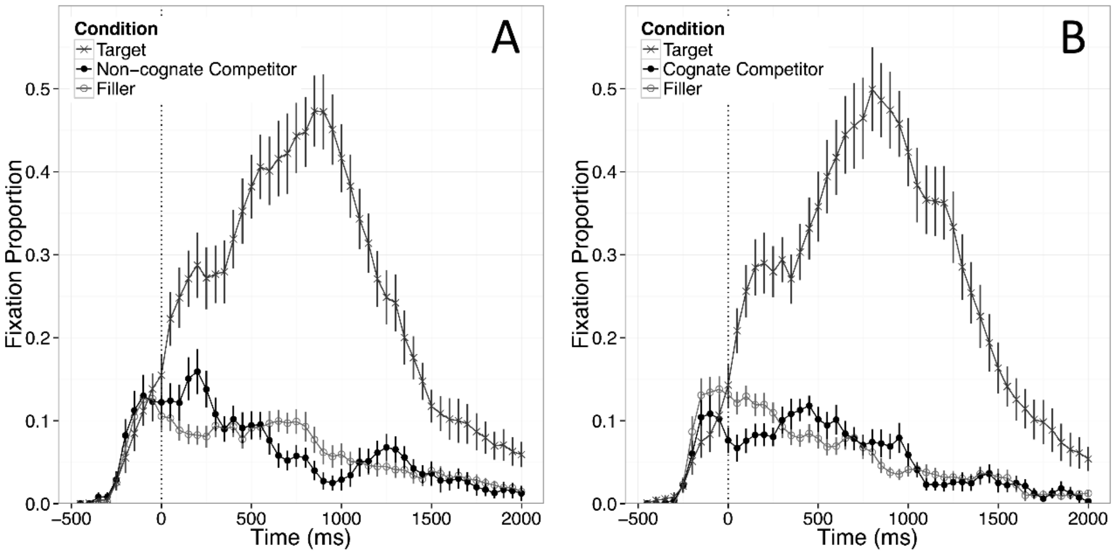

Figure 4. Visual fixations during cross-linguistic orthographic competition. Fixations to orthographic competitors was compared to filler items in a display using growth curve analysis in a window from word onset to peak target fixations (target identification). (A) Non-cognate competitors were analyzed from 0-850ms post word onset. (B) Cognate competitors were analyzed from 0-800ms post word onset.

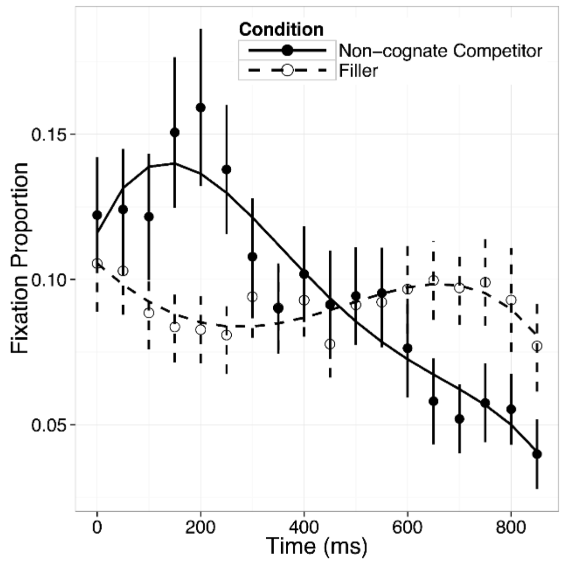

Figure 5. Non-cognate competitor and Filler picture fixations from 0 to 850ms post word onset. Participants were more likely to fixate pictures of English orthographic competitors (solid line, black circles) in response to auditory Colbertian target words; competitor fixations decreased over time more than fillers (dashed line, white circles), reflecting the initial competitor peak. Circles mark observed data, lines are fourth-order growth curve models.

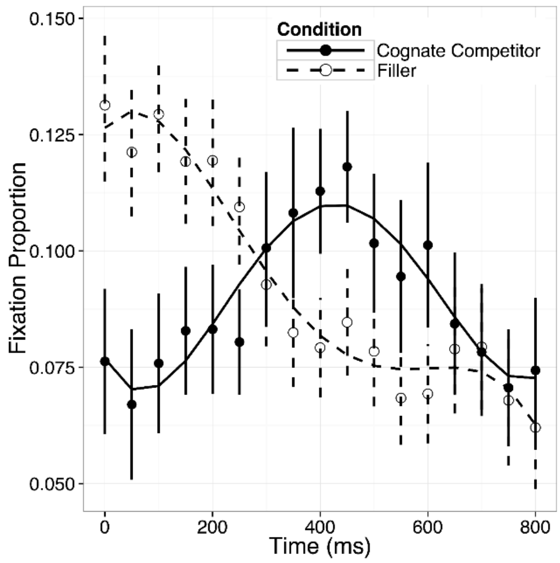

Figure 6. Cognate competitor and Filler picture fixations from 0 to 800ms post word onset. Fixations to pictures of English-Spanish cognate orthographic competitors (solid line, black circles) rose and fell in response to Colbertian auditory word targets, peaking 450ms post word onset. Fixations to pictures of non-overlapping filler items (dashed line, white circles), in contrast, decreased over the viewing window. Circles mark observed data, lines are fourth-order growth curve models.