Does bilingual experience influence statistical language learning?

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Abstract

Bilingual experience may confer advantages in statistical language learning tasks. Given that SL tasks can measure different aspects of foreign language learning, which aspects benefit from bilingual experience is still largely unexplored. Here, we compared a Spanish monolingual and two (Spanish-Basque and Spanish-English) bilingual groups across three well-established SL tasks. Each task targeted a different aspect of foreign language learning as a proxy—i.e., word segmentation, morphological rule generalization, and word-referent learning. In Experiment 1, we manipulated sub-lexical phonotactic patterns to vary the difficulty of three SL tasks, and the results showed no differences between the groups in word segmentation. In Experiment 2, we included non-adjacent dependencies to target affixal morphology rule learning, and again there were no differences between the groups. Finally, Experiment 3 addressed word learning using a more challenging audio-visual SL task combining exclusive and multiple word-referent mappings. We observed a bilingual experience effect only for the exclusive mappings but not for the multiple mappings. These results suggest that bilingual experience might mainly exert influences on statistical language learning at the lexical level. We discuss these findings by contextualizing SL as a cognitive mechanism, an experimental task, and a proxy for foreign language learning, highlighting the strengths and limitations in detecting bilingual experience effects.

Keywords: statistical learning, bilingualism, language learning

Does bilingual experience influence statistical language learning?

The human brain is remarkably susceptible to structure in the environment. Both infants and adults can quickly and implicitly learn from patterns presented repetitively, a mechanism broadly known as statistical learning (Saffran, 2003). Statistical learning occurs regardless of the input type (be it auditory, visual, or tactile), hinting towards a domain-general mechanism to track and learn from regularities in the environment (Kirkham et al., 2002). The field of language acquisition has taken a particular interest in *statistical language learning* (SL) as one of the primary mechanisms humans employ to implicitly learn languages (Perruchet & Pacton, 2006; Romberg & Saffran, 2010). However, the extent to which prior linguistic experiences affect SL remains largely unexplored. Here, we examined whether one of such linguistic experiences—namely, bilingualism—influences performance in SL tasks. In particular, we compared monolingual and bilingual adults in three well-established SL tasks that targeted different aspects of foreign language learning.

The idea of SL stems from observing the natural world. For example, with sufficient exposure to the words in the phrase *baby monkey*, infants and adults learn that the syllables within the words (i.e., *ba-by*) predict each other more reliably than the syllables at the boundary between the words (i.e., *by mo*) (Erickson & Thiessen, 2015). As an experimental task, SL consists of exposing participants to a continuous stream of artificial linguistic input and testing them on plausible—those that follow the statistics of the input—versus implausible items from the stream (Siegelman et al., 2017). Ideally, the participants should implicitly discover the boundaries between words solely from the statistics of the artificial language and mentally represent them as separate units. Researchers have employed this paradigm to examine how individuals implicitly learn different aspects of a novel language, including segmenting words

from speech (Saffran, 2003; Saffran et al., 1996), acquiring sub-lexical units (Maye et al., 2002; McMurray et al., 2009), discovering morphological rules (Frost & Monaghan, 2016; Peña et al., 2002), and learning word-referent pairs (Smith & Yu, 2008; Yu & Smith, 2007).

Individual linguistic experiences seem to influence performance in SL tasks. For instance, studies have shown that the stress pattern of the native language can interfere with SL performance in 9-month-old, but not in younger infants with less exposure to the native language (Jusczyk et al., 1999; Thiessen & Saffran, 2003). Adults also seem to struggle in SL tasks that contain syllables that are not plausible in their native language (Finn & Hudson Kam, 2008). Furthermore, the SL performance of both infants and adults seems to be biased towards the word order of their native language (Onnis et al., 2016; Onnis & Thiessen, 2013). Overall, it seems that the specific properties of a known language (e.g., stress patterns, word order) may facilitate or interfere with SL performance. It makes sense that prior linguistic experiences predispose the learning of novel linguistic material, as evidenced by cross-linguistic transfer studies (Alonso, 2016).

In bilingual adults—who consistently use two languages—, their practice with conflicting statistics may influence their performance in SL tasks. To put this idea to the test, Wang and Saffran (2014) compared two monolingual (English and Mandarin) and two bilingual (Mandarin-English, and English-Spanish) groups in a challenging SL task that combined syllables and tones to emulate a foreign tonal language. They found that, while the monolingual groups could not perform above chance level in this task, both bilingual groups outperformed monolinguals. They concluded that this “bilingual advantage” was irrespective of their experience with tonal languages and emerged from enhanced phonological working memory in bilinguals. Additional research has supported this idea using other challenging SL tasks, such as learning a Morse Code

language with interfering statistics (Bartolotti et al., 2011), simultaneous learning of two grammars (Onnis et al., 2018), and learning multiple word-referent pairs (Poepsel & Weiss, 2016). However, by using challenging SL tasks, all of these studies fail to disentangle the effects of SL task difficulty from those stemming from bilingual experience.

The present study

The literature presented so far highlights the influence of linguistic experience—particularly of bilingual experience—, on SL tasks. Given that SL tasks can measure different aspects of foreign language learning, several questions arise from this overview. First, if bilingual experience facilitates SL in general, do bilinguals show an overall advantage regardless of the specific SL task? Second, are the effects of bilingual experience modulated by the SL task difficulty? Third, do these effects emerge at specific levels of implicit foreign language learning? To address these questions, we compared monolingual and bilingual adults' performance across three SL experiments. The experiments targeted three aspects of foreign language learning as a proxy—i.e., word segmentation, morphological rule generalization, and word-referent learning—using well-established tasks reported in the literature. Given the consistency in published findings indicating the influence of bilingual experience on SL performance, our general hypothesis was that bilinguals should outperform their monolingual peers in the three tasks.

Critically, two bilingual groups were included in the study to isolate the effects of bilingual experience rather than specific language combinations. Spanish-English and Spanish-Basque bilinguals were compared to each other and against a Spanish monolingual group. All participants were from Spain, with Spanish-Basque bilinguals belonging to a different region (Basque Country) than the Spanish and Spanish-English groups (Murcia). While prior studies have emphasized the characteristics that differentiate Spanish and English, it is essential to

briefly comment on the commonalities and differences between the Spanish and Basque languages. Spanish and Basque do not share any common root, but Basque possesses many Spanish loan words due to their geographic proximity within Spain. Some language-specific bigrams differentiate Basque from Spanish (e.g., "tx", "tz"). However, the two languages are phonologically similar. The Basque language also possesses a predominantly subject-object-verb (SOV) word order, which involves a postpositional and agglutinative morphology—i.e., morphemes and determiners are appended to the end of word roots (e.g., *eskolan* – *school the in*). These properties differentiate Basque from Spanish, English, and many other Indo-European languages (Bengtson, 2011).

Experiment 1

Experiment 1 tested the word segmentation performance of monolinguals and bilinguals adults in three SL streams that differed in their sub-lexical phonotactic patterns. Phonotactics define the allowed combinations of phonemes in a given language. Studies have shown that violating the phonotactic patterns of the native language can hinder the word learning performance of infants and adults (Estes et al., 2016; Finn & Hudson Kam, 2008). For instance, exposing English-speaking adults to an SL stream containing syllables that do not exist in English (e.g., /*tfobu*/) leads to lower performance than stimuli that only contain plausible English syllables (Finn & Hudson Kam, 2008). Sublexical phonotactics—defined here as the plausibility of constituent syllables—provide an excellent way of adjusting the difficulty of SL tasks.

Bilinguals can potentially experience distinct phonotactics in both languages, affecting their word-learning performance (Kaushanskaya & Marian, 2009). Consequently, we expected both bilingual groups to show an advantage compared to monolinguals in this task. Additionally,

a specific question for this experiment was whether task difficulty could modulate this advantage. Therefore, participants in this experiment listened to three SL streams. The first one was constructed using simple consonant-vowel syllables, whereas the other two contained consonant clusters that were either legal or illegal.

Methods

Anonymized participant information, experimental data, materials, and annotated analyses scripts for all experiments are available at <https://osf.io/86sr4/>.

Participants

Forty Spanish monolinguals ($M_{\text{age}} = 21.8$, $SD = 2.6$; 37 females), forty Spanish-Basque bilinguals ($M_{\text{age}} = 21.2$, $SD = 1.9$; 35 females), and thirty-seven Spanish-English bilinguals ($M_{\text{age}} = 20.9$, $SD = 2.3$; 33 females) participated in this experiment. All participants reported normal or corrected-to-normal vision and no history of hearing or other neurological disorders. The study protocol was approved by the Ethics Committee of the Basque Center for Cognition, Brain and Language (BCBL) and carried out following the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans. Before their inclusion in the study, all subjects provided written informed consent. They received monetary compensation for their participation.

Before participating in the study, they completed a language background questionnaire, a picture-naming task, and a matrix reasoning task from the Kaufman Brief Intelligence Test (Kaufman & Kaufman, 2014) to measure non-verbal IQ. The linguistic questionnaire included information about the age of acquisition, total exposure to each language, self-rated proficiency scales for each known language, and demographic questions such as age and gender. The picture naming task consisted of sixty-five images from the Basque, English, and Spanish Test (BEST)

(de Bruin et al., 2017). Participants in the monolingual group named the images in Spanish and English, while the bilingual groups named them in both Spanish and their L2 (English or Basque). Additionally, participants in the bilingual groups completed the LexTALE test in Spanish and their respective L2 (Lemhöfer & Broersma, 2012). The combination of these tests provided information on receptive and productive L2 vocabulary in the bilingual groups.

We compared the three groups using several ANOVAs with Helmert contrasts. In other words, we contrasted the Spanish monolingual group against the two bilingual groups in the first level and both bilingual groups against each other in the second level. A complete table with demographic information and statistical comparisons can be found in Appendix A. The results suggested that the three groups did not differ in their age ($p = 0.204$, $BF_{10} = 0.303$), non-verbal IQ ($p = 0.619$, $BF_{10} = 0.303$), self-reported Spanish proficiency ($p = 0.419$, $BF_{10} = 0.166$) and Spanish picture naming ($p = 0.245$, $BF_{10} = 0.260$). As expected, the monolingual and bilingual groups differed in their exposure to Spanish, L2 age of acquisition, L2 exposure, L2 self-rated proficiency, and BEST picture naming in L2 (all $p < 0.001$). Crucially, the two bilingual groups did not differ in their L1 and L2 exposure, age of acquisition, self-rated proficiency, BEST picture naming, and LexTALE scores (all $p > 0.05$).

Materials

We constructed three auditory SL streams with eight trisyllabic words per stream. The syllables did not repeat within the streams, maintaining the transitional probabilities within the words at a constant value of 1. The eight words for each condition were randomly concatenated into continuous speech streams, with the constraint that there was no immediate word repetition and that each word appeared 80 times per stream.

The first of these streams, the *simple condition*, was only composed of consonant-vowel (CV) syllables and represented a version of the original statistical learning experiment (Saffran et al., 1996). An example of a word in this stream would be /*motufi*/. In the second and third conditions—or complex conditions—, each word contained one consonant cluster (CCV) syllable, either at the beginning or at the end of a word. The difference between these conditions was the sub-lexical phonotactic patterns that defined the syllables. In the *complex legal* condition, the consonant cluster in the syllable (i.e., /*fre*/, /*bla*/, /*fle*/, /*gli*/, /*gra*/, /*pre*/, /*pli*/, /*tre*/) were plausible at the beginning or end of a word without interfering with its segmentation (e.g., /*betafre*/). However, in the *complex illegal* condition, participants would hear words with consonant clusters that generally mark the boundary between syllables (i.e., /*rnu*/, /*gma*/, /*lgi*/, /*nfu*/, /*rbu*/, /*rfo*/, /*sfe*/, /*bsu*/) and were thus not plausible at the beginning or end of words (e.g., /*tenobsu*/). These consonant clusters were selected because they provided interfering cues—i.e., syllable boundaries—when inserted in an uninterrupted speech.

We synthesized the streams and each separate word using the MBROLA software (Dutoit et al., 1996), using the it3 voice, a constant pitch of 82.63Hz, and a duration of 200ms per syllable. No pauses were inserted between the words in any of the auditory streams. These constraints ensured minimal interference of segmentation cues due to varying pitch, amplitudes, or co-articulation of the syllables. Finally, following previous research, we introduced an amplitude ramp for the first and final 5 seconds of the stream (Onnis et al., 2016). It produced a fade-in and fade-out effect, giving the impression of an unbounded speech stream. The duration of each SL stream was around 7 minutes.

Procedure

Participants completed a familiarization phase followed by a 2-alternatives forced-choice (2AFC) test. They were asked to wear headphones and sit in a quiet room for the entire experiment. During the familiarization task, they listened to the artificial SL streams. As in prior studies, they were instructed to pay close attention to the made-up languages because later, they would answer questions about them (Saffran et al., 1999; Wang & Saffran, 2014). Each condition's order of presentation was counterbalanced for each participant. The 2AFC test immediately followed the familiarization phase in each condition. During this test, participants heard two words (one target and one foil) separated by 500 ms of silence and decided which of the words belonged to the previously heard language. The trials and the order of presentation of target and foil words were fully randomized. They responded using the keyboard (f and j keys) to indicate which word they thought was more similar to the previously heard language. The computer automatically recorded their accuracy during the experiment.

We included two types of foils during the test phase, synthesized in the same manner as the original words. The first type was non-words, created by inverting the syllables of the words in the stream. The second type of foils was part-words. We created these foils by combining the ending of one word and the beginning of another, maintaining the correspondence between syllables. For instance, at test, a word in the simple condition (/bukoni/) would be paired both with a non-word (/nikobu/) and with a part-word (/konito/) in separate trials. The inclusion of two types of foils allowed us to double the number of trials per condition to sixteen. With three familiarization and three test phases, the entire experiment lasted around 30 minutes. Participants were encouraged to take a small break between each condition. The tasks for this and the rest of the experiments were programmed in Psychopy (Peirce et al., 2019).

Data analysis

We analyzed participant's accuracy in the three SL streams using a generalized linear mixed model (GLMM). We assumed a binomial distribution and a logit link for the accuracy scores, with the Condition, Group, and their interaction as fixed effects of interest. The Condition factor was Helmert coded to contrast the simple against the complex conditions first and then contrast the two complex conditions against each other. Similarly, the Group factor was reverse Helmert coded according to our hypothesis. We first contrasted the two bilingual groups, expecting no differences between them. Then we contrasted both bilingual groups against the monolingual group. These factors were dummy-coded for each different contrast. Crucially, the contrasts were planned and coded explicitly according to our hypotheses. We decided to adopt a confirmatory approach—rather than an exploratory omnibus approach used in previous research—to evaluate the effects of bilingual experience in all experiments more robustly through a priori planned contrasts. This approach makes the GLMM analysis directly interpretable without the need for corrected post-hoc tests (Schad et al., 2020). The GLMM model was fitted using the *glmer* function from the “lme4” package in R (Bates et al., 2015). Following standard practice, we tried to fit the maximal random-effects structure and reduced it to achieve convergence by eliminating the correlations between random slopes or the random slopes themselves (Barr et al., 2013). The final model achieved convergence using the by-participant and by-item intercepts with by-participant uncorrelated slopes for the Condition factor.

Finally, we report both the frequentist and Bayesian versions of the tests where possible. We opted to report the results from the Bayesian framework because these provide robust tests of the differences between the groups while simultaneously testing for the null hypothesis (van Doorn et al., 2020). Exact p-values are reported up to the 0.001 level for frequentist tests. For

Bayesian tests, we report the exact Bayes Factor (BF_{10}) from 0.001 to 100. BF_{10} values below 1 indicate more support for the null hypothesis, and values above 1 support the alternative hypothesis. We used uninformative priors for all Bayesian analyses. Paired-, one-sample and independent-samples frequentist and Bayesian tests were conducted in JASP (Love et al., 2019). However, to obtain an approximate BF_{10} from the GLMM model, we contrasted nested models, including each fixed factor and interaction step-wise, against an intercept-only model with the same random-effects structure (Wagenmakers, 2007). In this case, the BF_{10} was calculated using the Bayesian Information Criterion (BIC) of the intercept-only (m_0) and each fixed-effect nested models (m_1) with the following formula:

$$BF_{10} = \exp\left(\frac{BIC(m_0) - BIC(m_1)}{2}\right)$$

Results and Discussion

We first tested whether the type of foil (i.e., non-words, part-words) influenced the SL tasks' results. Wilcoxon paired-samples tests over the aggregated accuracy suggested no differences between the non-word and part-word trials in the simple ($p = 0.764$, $BF_{10} = 0.106$), the complex legal ($p = 0.567$, $BF_{10} = 0.112$), or the complex illegal ($p = 0.992$, $BF_{10} = 0.104$) conditions. Thus, we did not include a type of foil factor in the GLMM analysis. As a second step, we tested whether participants' average accuracy score was above chance level (50%) in the three conditions using Wilcoxon one-sample tests. Participants in the Spanish monolingual group performed above chance level in the simple ($M_{acc} = 68.4$, $SD = 12.1$, $p < 0.001$, $BF_{10} > 100$), complex legal ($M_{acc} = 58.3$, $SD = 14.4$, $p < 0.001$, $BF_{10} > 100$), and complex illegal ($M_{acc} = 65.0$, $SD = 12.8$, $p < 0.001$, $BF_{10} > 100$) conditions. Participants in the Spanish-English bilingual group also performed above chance level in the simple ($M_{acc} = 62.5$, $SD = 14.8$, $p < 0.001$, $BF_{10} > 100$), complex legal ($M_{acc} = 65.5$, $SD = 11.4$, $p < 0.001$, $BF_{10} > 100$), and complex illegal (M_{acc}

270 = 60.1, $SD = 13.8$, $p < 0.001$, $BF_{10} > 100$) conditions. Similarly, participants in the Spanish-
271 Basque bilingual group performed above chance level in the simple ($M_{acc} = 67.3$, $SD = 17.7$, $p <$
272 0.001 , $BF_{10} > 100$), legal ($M_{acc} = 61.9$, $SD = 11.9$, $p < 0.001$, $BF_{10} > 100$), and illegal ($M_{acc} =$
273 60.6 , $SD = 13.1$, $p < 0.001$, $BF_{10} > 100$) conditions. Figure 1A presents the accuracy results by
274 group and condition. Notably, participants' average performance on each task (around 60-70%)
275 was in line with previous statistical learning studies reporting an average accuracy in the range of
276 55-70% (Erickson & Thiessen, 2015; Saffran, 2003).

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Figure 1*Average accuracy by condition and group in Experiment 1*

Note. Raincloud plots of accuracy scores. The center of the boxplot indicates the median, and the limits of the box define the interquartile range (IQR = middle 50% of the data) for each group. Dots reflect individual participant scores. The violin plots reflect the probability density of the scores. SP-EN = Spanish-English bilinguals; SP-BQ = Spanish-Basque bilinguals; MONO = Spanish monolinguals.

The GLMM analysis (shown in Table 1) indicated a significant difference between the simple and complex conditions ($p = 0.001$, $BF_{10} = 2.816$), but no significant differences between the two complex conditions ($p = 0.508$, $BF_{10} = 0.017$). Specifically, participants performed better in the simple than the complex conditions, without any differences in performance between the legal and illegal complex conditions. As expected, there were no differences between Spanish-Basque and Spanish-English bilingual groups ($p = 0.425$, $BF_{10} = 0.018$). However, the monolingual and bilingual groups did not differ in their performance ($p = 0.398$, $BF_{10} = 0.018$).

A significant two-way interaction indicated a difference between monolinguals and bilinguals in the complex conditions ($p = 0.010$, $BF_{10} = 0.329$). This interaction seemed to be driven by the monolingual group having a lower score in the complex legal compared to the complex illegal conditions and is not indicative of a bilingual experience effect since both bilingual groups had comparable performance in the two complex conditions.

Table 1
Accuracy GLMM results of Experiment 1

Fixed Effects		Estimate	SE	z	p	BF ₁₀
(Intercept)		0.551	0.070	7.909	< 0.001	-
Simple-Complex		0.071	0.022	3.288	0.001	2.816
Legal-Illegal		-0.023	0.034	-0.662	0.508	0.017
SPBQ-SPEN		0.036	0.045	0.797	0.425	0.018
MONO-BIL		0.022	0.026	0.845	0.398	0.018
Simple-Complex x SPBQ-SPEN		0.038	0.027	1.411	0.158	0.036
Simple-Complex x MONO-BIL		0.016	0.015	1.029	0.304	0.022
Legal-Illegal x SPBQ-SPEN		-0.012	0.042	-0.287	0.774	0.014
Legal-Illegal x MONO-BIL		-0.062	0.024	-2.566	0.010	0.329
Random Effects		Group		Variance	SD	
Item	(Intercept)			0.056	0.237	
Participant	(Intercept)			0.063	0.250	
	Simple-Complex			0.008	0.088	
	Legal-Illegal			0.002	0.040	

Note. Significant fixed effects terms are highlighted in bold. SE = standard error; SD = standard deviation; SPEN = Spanish-English bilinguals; SPBQ = Spanish-Basque bilinguals; MONO = Spanish monolinguals; BIL = bilinguals.

Experiment 1 revealed that more complex sub-lexical phonotactic patterns could modulate the word segmentation difficulty in SL tasks. All three groups, on average, performed the tasks above chance level. However, their performance was lower in the complex than the simple condition, with no differences between the two complex conditions. More importantly, the SL performance of monolingual and bilingual participants did not significantly differ in any of the conditions. A possible explanation for these findings is that we constructed the stimuli using syllables that naturally occur in Spanish, English, or Basque. Even if the complex illegal condition included syllables that could have interfered with the statistics in the speech stream,

these syllables also appear within words in all three languages. Therefore, our task may not have been challenging enough to elucidate the differences shown in previous studies (Bartolotti et al., 2011; Wang & Saffran, 2014). In other words, the bilingual experience might still come into play when the task is sufficiently challenging—i.e., by using tones or completely illegal phonotactic patterns—or produces interference with previously learned materials. With this in mind, in Experiment 2, we increased the difficulty of the task by testing monolinguals and bilinguals when extracting rules rather than specific words from an SL task designed as a proxy for morphological rule learning.

Experiment 2

In the previous experiment, learning the words largely depended on the transitional probabilities of adjacent syllables. Specifically, the patterns presented in these SL streams could not be generalized outside of their respective artificial speech streams. While language learning requires identifying and learning the patterns within and across different words, it also encompasses learning the morphological rules that bind them together. Learning these rules allows generalization to instances where the words vary due to their dependency on other constituents (Endress & Bonatti, 2016; Peña et al., 2002). The perfect example is affixal morphology, where structures append to the beginning (prefix) or ending (suffix) of a word to change its class or meaning (e.g., *untouchable*, *unbreakable*). These rules can span multiple elements, and in the SL literature, they are commonly known as non-adjacent dependencies (Misyak & Christiansen, 2007). Some authors posit similar SL mechanisms to those employed in word segmentation underly learning these non-adjacent dependencies (Frost & Monaghan, 2016; Misyak & Christiansen, 2007). However, to our knowledge, no prior study has addressed

whether bilingual experience can affect the implicit learning and generalization of non-adjacent dependencies.

In Experiment 2, we explored the capacity of monolinguals and bilinguals to learn non-adjacent dependencies from an SL stream and generalize them to novel items. Having observed no differences arising from bilingual experience in the first experiment, the purpose behind this manipulation was to test whether the groups would differ in another aspect of language learning by using this task as a proxy for morphological rule generalization. Since this task tested participants' generalization ability and was more challenging than the previous two tasks, we adhered to our original hypothesis and expected to find differences between the groups.

Methods

Participants

Forty Spanish monolinguals ($M_{\text{age}} = 21.7$, $SD = 2.4$; 35 females), forty Spanish-Basque bilinguals ($M_{\text{age}} = 21.8$, $SD = 2.2$; 32 females), and forty Spanish-English bilinguals ($M_{\text{age}} = 21.0$, $SD = 2.4$; 36 females) participated in Experiment 2. Participants had a similar profile as those in Experiment 1. Appendix B shows the demographic information and statistical contrasts between groups.

Materials

We concatenated nine words with an AXC form, where A and C established a frame with constant syllables, and X was a filler syllable that could vary. Following previous work (Frost & Monaghan, 2016), we used plosive syllables for the A_C frames (/ke/, /po/, /bi/, /ga/, /du/, /ti/) and continuants for the X fill syllables (/mu/, /fe/, /li/). The frame syllables were randomized to create five counterbalanced versions of the SL stream. There were three different frames combined with the three fill syllables, creating nine words for each version. We manually

verified that none of the streams contained words or parts of words that existed in Spanish, English, or Basque. There were 100 repetitions of each word in every version of the stream. We synthesized the streams in the same manner as in Experiment 2, ensuring this time that there were no immediate repetitions of words with the same frame. The overall duration of the speech streams was about 12 minutes.

Procedure

The procedure was identical to the previous experiment except for the test trials. For the 2AFC test, we used three continuant syllables as generalization fills (/se/, /ya/, /ni/) and inserted them in the original frames to produce nine AYC generalization words. We tested participants on their ability to distinguish these words from three types of foils. The first two types were part-words created by concatenating the ending of the target word and the beginning of a different word from the stream. For example, a target word (/kenipo/) would be paired with a part-word starting at the fill syllable (/nipoti/) or ending with the fill syllable (/gakeni/). The last type of trials were non-words, created by inverting the word's syllables (e.g., /ponike/). Due to the randomized nature of the different versions, a target word in one of the lists could potentially be a non-word foil in any other version. The inclusion of three types of tests increased the number of trials to 27, representing a substantial increase from the previous experiment.

Data analysis

The data analysis closely followed Experiment 1, the only difference being that there were no conditions.

Results and Discussion

As a first step, we tested whether the list or the type of foil influenced average performance in the task. An ANOVA suggested similar performance regardless of the stream's

version ($p = 0.069$; $BF_{10} = 0.535$) and the type of foil ($p = 0.527$, $BF_{10} = 0.052$), and no interaction between the two ($p = 0.217$, $BF_{10} = 0.009$). Furthermore, Wilcoxon one-sample tests against chance-level indicated that participants in the monolingual ($M_{acc} = 59.1$, $SD = 17.5$, $p = 0.011$, $BF_{10} > 100$), Spanish-English ($M_{acc} = 57.3$, $SD = 13.4$, $p = 0.005$, $BF_{10} > 100$), Spanish-Basque ($M_{acc} = 60.1$, $SD = 15.1$, $p < 0.001$, $BF_{10} > 100$) groups performed above the 50% chance-level in the task. Figure 2 depicts the results by group. In this case, the GLMM revealed no differences between the two bilingual groups (Estimate = 0.066, $SE = 0.077$, $z = 0.858$, $p = 0.391$, $BF_{10} = 0.025$), or between the monolingual and bilingual groups (Estimate = 0.009, $SE = 0.044$, $z = 0.216$, $p = 0.829$, $BF_{10} = 0.018$).

Figure 2*Average accuracy by Group in Experiment 2*

Note. Raincloud plots of accuracy scores. The center of the boxplot indicates the median, and the limits of the box define the interquartile range (IQR = middle 50% of the data) for each group. Dots reflect individual participant scores. The violin plots reflect the probability density of the scores. SP-EN = Spanish-English bilinguals; SP-BQ = Spanish-Basque bilinguals; MONO = Spanish monolinguals.

Overall, Experiment 2 extended the findings from the previous experiment by testing the generalization of non-adjacent dependencies learned during an SL task as a proxy for morphological rule learning. In line with previous studies, participants could generalize the frames extracted from the artificial language above chance-level, hinting towards similar implicit mechanisms for word and rule learning (Endress & Bonatti, 2016; Frost & Monaghan, 2016). However, the focal point of Experiment 2 was to compare the performance of bilinguals and monolinguals in generalizing information from the SL task. The main challenge of this

experiment was that participants needed to extract the non-adjacent frames from the stream—rather than specific words—and generalize this knowledge to novel items. Nevertheless, our results indicated similar performance between the three groups and thus no bilingual experience effects.

Spanish and Basque possess a rich morphology at the verb and noun levels (García Mayo & Villarreal Olaizola, 2011). Although English has a less rich morphology than Spanish and Basque, participants in the Spanish-English group might have benefited from their native knowledge of Spanish. In other words, the three languages may not differ sufficiently in their affixal morphology, such as to affect the non-adjacent dependencies generalization measured by this SL task. Notably, we did not target any specific differences that long-term speakers of two languages might exploit for a learning advantage. Thus, even if the task was more challenging and addressed a different aspect of language compared to the previous experiment, we still did not observe effects stemming from the bilingual experience. A possibility raised by prior work is that bilingual experience might mainly influence learning at the lexical level (Kaushanskaya & Marian, 2009; Poepsel & Weiss, 2016). Hence, in Experiment 3, we presented participants with an audio-visual SL task targeting word-referent learning.

Experiment 3

Studies have shown that, through SL mechanisms, infants and adults can learn mappings between words and visual referents (objects) across multiple scenarios, an ability known as cross-situational (CS)SL (Smith & Yu, 2008; Yu & Smith, 2007). The CSSL task differs from other SL tasks because participants learn the names for different visual referents by aggregating information through multiple contexts. In other words, they implicitly “discover” each object’s

name by seeing it in conjunction with other distinct referents. This task was designed to mimic the crowded visual world where infants initially learn words (Yu & Smith, 2007). It seems to target a crucial implicit mechanism for learning words in native and foreign languages (Benitez et al., 2016; Smith & Yu, 2008).

Perhaps one of the defining characteristics of bilingual experience is learning to map one referent to two potentially different words (e.g., *perro* – *dog/txakur*), but this phenomenon is not unique to bilingualism and happens within languages. For instance, there are concepts with multiple names or *synonyms* (e.g., *paper* – *sheet*) and words with multiple referents or *homonyms* (e.g., *bat* as the animal or the object). Bilinguals have the added difficulty of learning these two types of mappings within two languages and across languages, potentially influencing their ability to learn them. Prior work has shown that bilinguals can outperform monolinguals in a CSSL task when learning homonyms (i.e., one word to two referents), but not when learning exclusive one-to-one mappings (Poepsel & Weiss, 2016). Other authors only report differences between bilinguals and monolinguals in the one-to-one mappings (Escudero et al., 2016). Finally, some have only found minimal differences between bilinguals and monolinguals learning one-to-one and synonym (i.e., two words to one referent) mappings (Benitez et al., 2016).

To address these discrepant findings, in Experiment 3, we compared monolinguals and bilinguals in a CSSL task that entailed learning one-to-one, two-to-one (synonyms), and one-to-two (homonyms) word-referent pairs. If bilingual experience facilitates overall word learning, participants in the bilingual groups should outperform those in the monolingual group in the one-to-one mappings. However, if bilingual experience only potentiates learning multiple word-

referent mappings, they should perform better than monolinguals in the more challenging multiple mapping conditions.

Methods

Participants

Forty Spanish monolinguals ($M_{\text{age}} = 21.7$, $SD = 2.5$; 37 females), forty Spanish-Basque bilinguals ($M_{\text{age}} = 21.9$, $SD = 1.9$; 31 females), and thirty-seven Spanish-English bilinguals ($M_{\text{age}} = 21.0$, $SD = 2.4$; 32 females) participated in Experiment 3. Participants had a similar profile as those in Experiment 1. Appendix C shows the demographic information and statistical contrasts between groups.

Materials

We created 30 words by randomly concatenating letters from a pool of consonants (t, l, k, m, n, b, s, p, g, d) and vowels (a, i, u, e, o) in an alternating manner. The words had either a CVCVCV (e.g., /ninugo/) or a VCVCV (e.g., /udili/) form and were synthesized using the Mac OS X system's Text-to-Speech software with the Spanish female voice "Monica". Since these words were presented in isolation, we did not enforce as much control (e.g., constant pitch, vowel duration) as in the previous three experiments, thus creating more natural-sounding stimuli. We eliminated words that existed or sounded like actual Spanish, English, or Basque words from an initial list. The final 30 words were paired with 30 color depictions of non-existing objects manually selected from the NOUN database (Horst & Hout, 2016) based on their color saliency and visual complexity scores.

The critical manipulation in this task involved creating the different word-referent mappings. As shown in Figure 3, twelve words were randomly paired with twelve objects to form the *exclusive* (one-to-one) mappings. For the *homonym* (one-to-two) mappings, we

randomly paired six words and twelve objects, producing words with two distinct referents. Conversely, for the *synonym* (two-to-one) mappings, twelve words were randomly paired with six objects, such that each of these objects had two different names. We manually verified that the words and objects in the multiple mapping conditions were not very similar to avoid artificially increasing task difficulty.

Figure 3
Word-referent mappings in Experiment 3

Note. The leftmost panel depicts an example of the Exclusive one-to-one mappings, where one word was consistently presented with one visual referent. The middle panel illustrates an example of a Homonym one-to-two mapping, where one word was paired with two distinct visual referents. The rightmost panel shows an example of a Synonym two-to-one mapping, where two words referred to the same visual referent. The depicted words are actual examples from the experiment, but we replaced the objects from the NOUN dataset with simple geometric figures for illustrative purposes.

Procedure

Participants completed three blocks of alternating familiarization and test phases. As in previous experiments, they were asked to wear headphones and sit in a quiet room. In each familiarization phase, they saw thirty-two scenes composed of three objects horizontally aligned at the center of the screen over a white background. They also heard the three names for the depicted objects in each scene, starting after one second and with a one-second pause between them. Participants were instructed to pay attention to the different scenes because they would later perform a test based on them. The objects' position and the order of the audios were fully randomized in each scene so that there was no particular match between words and referents. Following previous studies (Poepsel & Weiss, 2016), only one side of the multiple mappings was

presented during the first half of the scenes. During the second half, the other side of the multiple mappings was shown, simulating a change of context. This manipulation allowed us to test the effects of primacy and recency on the multiple mappings. We created four counterbalanced lists by varying which side of the two multiple mapping conditions was presented during the first and second halves of the familiarization phase. Thus, the scenes' order of presentation was pseudo-randomized for each familiarization phase so that no word or referent, including two sides of the multiple mappings, would appear in contiguous scenes.

Following each familiarization phase, participants completed a 2AFC test. In each trial, two horizontally-aligned objects (one target and one foil) were presented, and the target object's name was played. The trials' order of presentation and the position of target and foil objects were fully randomized. Participants were instructed to select the object they thought corresponded to the heard name using the keyboard ("f" and "j" keys). The one-to-one mappings were tested during the three test blocks. However, during the first two experimental blocks, only one side of the multiple mappings was presented, corresponding to the order of presentation during the familiarization phase (Poepsel & Weiss, 2016). The complete word-referent list was used for the last block, controlling that the foil object did not correspond to the multiple mapping condition. The entire experiment lasted about 45 minutes, and participants were encouraged to take small breaks between each block.

Data analysis

We modeled the exclusive and multiple (synonyms/homonyms) mappings data separately using GLMMs, similar to the previous two experiments. For the exclusive mappings, we treated the block as a continuous linear factor and compared the reverse Helmert-coded groups and their interaction with the blocks as fixed effects. In this case, the GLMM was performed over the

proportion correct data to avoid inflating the estimates for the linearized block (Mirman, 2017). As in the previous experiments, we contrasted the Spanish-Basque against the Spanish-English group first, and then both bilingual groups against monolinguals. We included the group, the block, and their interactions as fixed effects and the by-participant intercept and uncorrelated block slope as random effects.

For the more challenging multiple mappings, since participants were tested on different mapping sides during the first and second blocks, we only contrasted the groups in the final test at block three. We created a factor to account for the order of presentation in the CSSL task. During the familiarization phase, the mappings displayed first represented the *primacy* mappings, and those displayed later the *recency* mappings. The group contrasts were the same as for the exclusive mappings. We tested the order-of-presentation factor and its interactions with the group as fixed effects. We included the by-participant and by-item intercepts and the by-participant slope for order of presentation as random effects in the final GLMMs.

Results and Discussion

Before the analysis, we removed one participant from the monolingual group with chance level performance in all three exclusive blocks. We first confirmed there were no differences between the lists across the three blocks on the exclusive mappings, as the counterbalanced lists only targeted the multiple mappings. A series of ANOVAs revealed that there were no differences due to the list in the first ($p = 0.901$, $BF_{10} = 0.058$), second ($p = 0.586$, $BF_{10} = 0.096$), or third block ($p = 0.815$, $BF_{10} = 0.066$). Next, we compared participants' accuracy on the Exclusive mappings to chance level (50%) in the last block. Wilcoxon one-sample tests indicated that Spanish monolinguals ($M_{acc} = 83.1$, $SD = 14.6$, $p < 0.001$, $BF_{10} > 100$), Spanish-English bilinguals ($M_{acc} = 86.9$, $SD = 14.2$, $p < 0.001$, $BF_{10} > 100$), and Spanish-Basque bilinguals (M_{acc}

544 = 91.0, SD = 10.2, $p < 0.001$, $BF_{10} > 100$) performed significantly above chance level. Figure 4A
545 depicts the accuracy for each group across the three blocks. Notably, accuracy was higher for
546 this task than in the previous experiments.

547

Figure 4
Average accuracy by group and block in Experiment 3

Note. (A) Accuracy by group and block in the one-to-one (Exclusive) mappings. (B) Accuracy by group, mapping type, and order of presentation for the multiple (Homonyms and Synonyms) mappings. The center of the boxplot indicates the median, and the limits of the box define the interquartile range (IQR = middle 50% of the data) for each group. Dots reflect individual participant scores. The violin plots reflect the probability density of the scores. SP-EN = Spanish-English bilinguals; SP-BQ = Spanish-Basque bilinguals; MONO = Spanish monolinguals.

Table 3*Accuracy GLMM results of exclusive condition in Experiment 4*

Fixed Effects	Estimate	SE	z	p	BF ₁₀
(Intercept)	1.411	0.064	22.141	< 0.001	-
Block	0.938	0.076	12.371	< 0.001	> 100
SPBQ-SPEN	0.149	0.078	1.927	0.054	0.190
MONO-BIL	-0.124	0.043	-2.886	0.004	1.902
Block x SPBQ-SPEN	0.163	0.095	1.720	0.085	0.079
Block x MONO-BIL	-0.079	0.051	-1.542	0.123	0.061
Random Effects	Group	Variance	SD		
Participant	(Intercept)	0.250	0.500		
	Linear	0.059	0.243		

Note. Significant fixed effects terms are highlighted in bold. SE = standard error; SD = standard deviation; SPEN = Spanish-English bilinguals; SPBQ = Spanish-Basque bilinguals; MONO = Spanish monolinguals; BIL = bilinguals.

Table 3 shows the results for the exclusive mappings' GLMM. Unsurprisingly, the analysis revealed a significant effect of the block ($p < 0.001$, $BF_{10} > 100$), indicating that participant's accuracy increased across the three blocks. The results also indicated no significant differences between the two bilingual groups ($p = 0.054$, $BF_{10} = 0.190$). However, there were significant differences between monolinguals and bilinguals ($p = 0.004$, $BF_{10} = 1.902$). The interactions between block and group did not reach statistical significance ($p = 0.085$, $BF_{10} = 0.079$; $p = 0.123$, $BF_{10} = 0.061$; respectively).

In the homonym condition (Figure 4B, left), Wilcoxon one-sample tests indicated that participants in the monolingual ($M_{acc} = 82.3$, $SD = 14.6$, $p < 0.001$, $BF_{10} > 100$), Spanish-Basque ($M_{acc} = 87.1$, $SD = 12.1$, $p < 0.001$, $BF_{10} > 100$), and Spanish-English ($M_{acc} = 80.6$, $SD = 17.9$, $p < 0.001$, $BF_{10} > 100$) groups performed above the 50% chance level on average. The GLMM results for the homonym mappings indicated a significant effect of the order of presentation (Estimate = -0.359, SE = 0.113, $z = -3.173$, $p = 0.002$, $BF_{10} = 4.874$), where performance in the recency mappings was, on average, better than in the primacy mappings. There were no differences between the two bilingual groups (Estimate = 0.236, SE = 0.145, $z = 1.627$, $p = 0.104$, $BF_{10} = 0.148$), or between the monolingual and bilingual groups (Estimate = -0.063, SE =

0.082, $z = -0.769$, $p = 0.442$, $BF_{10} = 0.034$). There were no significant interactions between the order of presentation and the group contrasts (all $p > 0.05$, $BF_{10} < 0.1$).

In the synonym condition, (Figure 4B, right), Wilcoxon one-sample tests indicated that participants in the monolingual ($M_{acc} = 67.7$, $SD = 16.0$, $p < 0.001$, $BF_{10} > 100$), Spanish-Basque ($M_{acc} = 73.5$, $SD = 14.2$, $p < 0.001$, $BF_{10} > 100$), and Spanish-English ($M_{acc} = 66.9$, $SD = 13.5$, $p < 0.001$, $BF_{10} > 100$) groups performed above the 50% chance level on average. The GLMM for this condition revealed an effect of order of presentation in the same direction as for the homonym mappings (Estimate = -0.286 , $SE = 0.068$, $z = -4.211$, $p < 0.001$, $BF_{10} > 100$). However, in this case, the analysis revealed a marginally significant difference between Spanish-Basque and Spanish-English bilinguals (Estimate = 0.174 , $SE = 0.086$, $z = 2.023$, $p = 0.043$, $BF_{10} = 0.211$), and no difference between monolinguals and bilinguals (Estimate = -0.037 , $SE = 0.079$, $z = -0.752$, $p = 0.452$, $BF_{10} = 0.037$). As in the homonym condition, there were no significant interactions between the order of presentation and the group contrasts (all $p > 0.05$, $BF_{10} < 0.1$). Additionally, a Wilcoxon paired-samples test confirmed that accuracy was overall higher in the homonym than in the synonym mappings ($p < 0.001$, $BF_{10} > 100$).

Overall, Experiment 3 indicated that participants could learn the exclusive mappings and the two types of multiple mappings from the same audio-visual CSSL task. Contrary to our two previous experiments, this design also allowed us to test participants' learning at three stages, showing a progressive increase in their performance for the exclusive mappings. In this regard, both bilingual groups outperformed the monolingual group on the exclusive one-to-one mappings. Thus, our results align with prior findings suggesting bilingual experience effects for these types of mappings in CSSL and other explicit word-learning tasks (Escudero et al., 2016; Kaushanskaya & Marian, 2009). However, these findings should be interpreted in the context of

the more challenging multiple mappings. The task itself was more demanding than the previous experiments—i.e., participants had to learn thirty novel items and words with different mappings in an implicit manner. Therefore, it is unclear whether the observed bilingual experience effect is constrained to the exclusive mappings or emerged due to the conflicting multiple mapping conditions.

Despite a similar design, our results diverge from prior work reporting bilingual experience effects in the homonym but not in the exclusive mappings (Poepsel & Weiss, 2016). The homonym mappings were easier to acquire for our participants than the synonym mappings, and there were no differences between monolinguals and bilinguals on these multiple mapping conditions. A possible reason for these findings is that pure synonyms—especially those referring to concrete objects with the same meaning—are significantly rarer than homonyms in most natural languages (Hurford, 2003). Moreover, it is often necessary to introduce additional cues, such as speaker identity or spacing between presentations, to avoid direct competition from multiple mappings during learning (Benitez et al., 2016). Out of these two factors, we only spaced the multiple mappings' presentations during the learning phase, leading to the observed difference between primacy and recency mappings extensively reported in associative learning research (Pineño & Miller, 2005). These results suggest exciting avenues for investigating the role of other cues in how bilinguals and monolinguals learn multiple mappings, but these remain beyond the scope of our study.

General Discussion

The present study examined the effects of bilingual experience across three statistical language learning (SL) experiments. We opted to use three well-established SL tasks to

approximate different aspects of foreign language learning as a proxy, including word segmentation from continuous speech (Experiment 1), morphological rule generalization (Experiment 2), and word-referent learning (Experiment 3). The inclusion of two bilingual groups and different manipulations allowed us to disentangle the overall effects of bilingual experience from those stemming from task difficulty or specific language pairs. Additionally, our confirmatory analytical approach and sample size—of almost three times the size reported in the literature—facilitated the straightforward evaluation of our central hypothesis.

Overall, Experiment 1 showed that, while manipulating the sub-lexical phonotactics of the SL stream affected participants' performance, there were no bilingual experience effects for word segmentation. In Experiment 2, participants generalized the learned non-adjacent dependencies during the test phase, but again, we did not find any bilingual experience effects. Lastly, in Experiment 3, we tested participants' ability to learn exclusive and multiple word-referent pairs across three blocks. The results revealed that bilingual participants outperformed their monolingual peers when learning the exclusive but not the multiple word-referent mappings. Notably, in all experiments, regardless of the manipulation, the average performance of all groups was significantly above chance and in the range reported in the literature (Erickson & Thiessen, 2015; Perruchet & Pacton, 2006; Saffran, 2003), which points to the robustness of SL as an implicit mechanism for foreign language learning.

It is essential to distinguish SL as a cognitive mechanism, an experimental task, and a proxy for foreign language learning. As a cognitive mechanism, other individual differences could perhaps account for auditory SL performance better than the bilingual experience, such as spontaneous synchronization to speech (Assaneo et al., 2019). In other words, some intrinsic particularities of the cognitive system could influence SL as a cognitive mechanism. Also,

bilingual experience effects may be reduced or eliminated in the absence of interfering information. Experiments 1 and 2 showed no bilingual experience effects, but the differences in Experiment 3 could have emerged in the context of the more difficult multiple mapping conditions. Prior studies seem to support this idea, showing bilingual experience effects only when participants learn from interfering SL streams (Bartolotti et al., 2011; Onnis et al., 2018). However, the purpose of this study was to isolate the effects of bilingual experience from other factors (e.g., task difficulty, interference, specific language properties) previously shown in the literature (Bartolotti et al., 2011; Onnis et al., 2018; Wang & Saffran, 2014). In doing so, we purposefully refrained from introducing additional variables that could more likely benefit from the bilingual experience. For instance, other studies have shown that bilingual experience could influence non-native phonetic learning and conflict resolution (Antoniou et al., 2015; Donnelly et al., 2015). These abilities could indirectly affect SL as a cognitive ability, but whether they account for bilingual experience effects in SL tasks remains to be explored.

Considering SL simply as an experimental task, participants are sensitive to specific and controlled manipulations of the probabilities between and within words that might target properties of a specific language (Finn & Hudson Kam, 2008; Onnis & Thiessen, 2013). Consequently, any bilingual experience effects may primarily rely on the properties of participants' known languages and not the overall bilingual experience. Moreover, bilingual experience effects might emerge progressively through learning, and one-shot 2AFC tests are not sensitive enough to capture them. Most SL studies base their results on a single familiarization and test phase, constraining their findings to what is learned upon first exposure to a foreign language (Romberg & Saffran, 2010). A common criticism with this approach is that performance, as measured by a one-shot 2AFC test, is highly variable and noisy, partly due to

the low number of trials generated from these artificial streams (Siegelman & Frost, 2015). In other words, there usually are only a handful of target and foil words presented during the test phase, and using a single test introduces additional variability in participants' scores. Thus, while these experimental tasks could be adequate to measure learning at the group level, they might not be sensitive enough to detect individual differences (Siegelman & Frost, 2015). Notably, we partially addressed these limitations in Experiment 3 by adding three familiarization and test phases for the twelve exclusive mappings and found differences between monolinguals and bilinguals. However, observing any effects in other SL tasks might be unlikely due to the variability in responses from one-shot 2AFC tests. Future research could further address these gaps by using continuous measures to focus on the process rather than the learning outcome.

Lastly, considering SL as a proxy for foreign language learning, bilingual experience effects might arise mainly at the lexical level. Most of the literature supporting a bilingual advantage primarily focuses on explicit vocabulary learning tasks, highlighting that bilinguals might more easily establish links between new word forms (orthographic or phonological) and their meanings within the mental lexicon than monolinguals (Antoniou et al., 2015; Kaushanskaya & Marian, 2009). In this regard, the present study showed no bilingual experience effects using SL tasks as proxies for word segmentation and morphological levels. However, there were significant differences at the lexical level in the word-referent learning task. Our results extend prior findings by introducing synonyms and homonyms and showing that participants can learn these multiple mappings from the same implicit task but with no differences between monolinguals and bilinguals. Since experimental work seldom targets other aspects of language (e.g., grammar, syntax), it would be interesting to explore whether bilingual

experience effects are constrained to the lexical level or extend to more higher-level aspects of a foreign language.

Conclusion

Does bilingual experience influence statistical language learning? Our answer is that it depends. Statistical learning is a robust cognitive process supported by a plethora of experimental findings. At the same time, decisions about stimuli selection, experiment design, participant selection, data collection, and statistical analysis can significantly influence the outcome and interpretation of SL experiments. Our study explores only a handful of manipulations that could have potentially elicited bilingual experience effects, such as experience with different phonotactic patterns, the ability to generalize learned knowledge, and the capacity to learn exclusive and multiple word-referent pairs. Crucially, SL only accounts for a minimal part of what learning a new language entails. Adult individuals acquire a significant part of a foreign language through explicit processes, and implicit learning might play a more prominent role after individuals have achieved a certain proficiency level in a new language (Ellis, 2015). However, the question of whether bilingual experience can influence SL as a cognitive mechanism is perhaps ill-posed. Instead, to make progress in this field, we believe studies should focus on how life experiences affect the strategies and filters through which individuals implicitly process and learn from linguistic and non-linguistic material.

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Competing interests statement

The authors declare no financial, commercial, or institutional competing interests.

CRedit author contribution statement

JAA: Conceptualization, Methodology, Software, Investigation, Resources, Data Curation, Formal analysis, Writing – Original Draft, Visualization, Project administration, and Funding acquisition **MC:** Conceptualization, Methodology, Writing – Review & Editing, Supervision, Project administration, and Funding acquisition.

Open Practices statement

Anonymized participant information, experimental data, materials, and annotated analyses scripts for all experiments are freely available at <https://osf.io/86sr4/>. This study was not preregistered.

References

- Alonso, R. A. (2016). Cross-linguistic influence in second language acquisition. In *Multilingual Matters*. <https://doi.org/10.1002/9781405198431.wbeal0292>
- Antoniou, M., Liang, E., Ettlinger, M., & Wong, P. C. M. (2015). The bilingual advantage in phonetic learning. *Bilingualism*, 18(4), 683. <https://doi.org/10.1017/S1366728914000777>
- Assaneo, M. F., Ripollés, P., Orpella, J., Lin, W. M., de Diego-Balaguer, R., & Poeppel, D. (2019). Spontaneous synchronization to speech reveals neural mechanisms facilitating language learning. *Nature Neuroscience*, 22(4), 627–632. <https://doi.org/10.1038/s41593-019-0353-z>
- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, 68(3), 255–278. <https://doi.org/10.1016/j.jml.2012.11.001>
- Bartolotti, J., Marian, V., Schroeder, S. R., & Shook, A. (2011). Bilingualism and inhibitory control influence statistical learning of novel word forms. *Frontiers in Psychology*, 2, 324. <https://doi.org/10.3389/fpsyg.2011.00324>
- Bates, D., Mächler, M., Bolker, B. M., & Walker, S. C. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*. <https://doi.org/10.18637/jss.v067.i01>
- Bengtson, J. (2011). The Basque Language: History and Origin. *International Journal of Modern Anthropology*, 1(4), 43–59. <https://doi.org/10.4314/ijma.v1i4.3>
- Benitez, V. L., Yurovsky, D., & Smith, L. B. (2016). Competition between multiple words for a referent in cross-situational word learning. *Journal of Memory and Language*, 90, 31–48. <https://doi.org/10.1016/j.jml.2016.03.004>
- de Bruin, A., Carreiras, M., & Duñabeitia, J. A. (2017). The BEST dataset of language

- 755 proficiency. *Frontiers in Psychology*, 8, 522. <https://doi.org/10.3389/fpsyg.2017.00522>
- 756 Donnelly, S., Brooks, P. J., & Homer, B. D. (2015). Examining the Bilingual Advantage on
757 Conflict Resolution Tasks: A Meta-Analysis. *CogSci*.
- 758 Dutoit, T., Pagel, V., Pierret, N., Bataille, E., & van der Vrecken, O. (1996). MBROLA project:
759 Towards a set of high quality speech synthesizers free of use for non commercial purposes.
760 *Proceeding of Fourth International Conference on Spoken Language Processing, ICSLP*,
761 1393–1396. <https://doi.org/10.1109/icslp.1996.607874>
- 762 Ellis, N. C. (2015). *Implicit AND explicit language learning*.
763 <https://doi.org/10.1075/sibil.48.01ell>
- 764 Endress, A. D., & Bonatti, L. L. (2016). Words, rules, and mechanisms of language acquisition.
765 *Wiley Interdisciplinary Reviews: Cognitive Science*, 7(1), 19–35.
766 <https://doi.org/10.1002/wcs.1376>
- 767 Erickson, L. C., & Thiessen, E. D. (2015). Statistical learning of language: Theory, validity, and
768 predictions of a statistical learning account of language acquisition. *Developmental Review*,
769 37, 66–108. <https://doi.org/10.1016/j.dr.2015.05.002>
- 770 Escudero, P., Mulak, K. E., Fu, C. S. L., & Singh, L. (2016). More limitations to
771 monolingualism: Bilinguals outperform monolinguals in implicit word learning. *Frontiers*
772 *in Psychology*, 7, 1218. <https://doi.org/10.3389/fpsyg.2016.01218>
- 773 Estes, K. G., Gluck, S. C. W., & Grimm, K. J. (2016). Finding patterns and learning words:
774 Infant phonotactic knowledge is associated with vocabulary size. *Journal of Experimental*
775 *Child Psychology*, 146, 34–49. <https://doi.org/10.1016/j.jecp.2016.01.012>
- 776 Finn, A. S., & Hudson Kam, C. L. (2008). The curse of knowledge: First language knowledge
777 impairs adult learners' use of novel statistics for word segmentation. *Cognition*, 108(2),

- 778 477–499. <https://doi.org/10.1016/j.cognition.2008.04.002>
- 779 Frost, R. L. A., & Monaghan, P. (2016). Simultaneous segmentation and generalisation of non-
780 adjacent dependencies from continuous speech. *Cognition*, 147, 70–74.
781 <https://doi.org/10.1016/j.cognition.2015.11.010>
- 782 García Mayo, M. D. P., & Villarreal Olaizola, I. (2011). The development of suppletive and
783 affixal tense and agreement morphemes in the L3 english of basque-spanish bilinguals.
784 *Second Language Research*, 27(1), 129–149. <https://doi.org/10.1177/0267658310386523>
- 785 Horst, J. S., & Hout, M. C. (2016). The Novel Object and Unusual Name (NOUN) Database: A
786 collection of novel images for use in experimental research. *Behavior Research Methods*,
787 48(4), 1393–1409. <https://doi.org/10.3758/s13428-015-0647-3>
- 788 Hurford, J. R. (2003). Why synonymy is rare: Fitness is in the speaker. *Lecture Notes in*
789 *Artificial Intelligence (Subseries of Lecture Notes in Computer Science)*, 442–451.
790 https://doi.org/10.1007/978-3-540-39432-7_47
- 791 Jusczyk, P. W., Houston, D. M., & Newsome, M. (1999). The Beginnings of Word Segmentation
792 in English-Learning Infants. *Cognitive Psychology*, 39(3–4), 159–207.
793 <https://doi.org/10.1006/cogp.1999.0716>
- 794 Kaufman, A. S., & Kaufman, N. L. (2014). Kaufman Brief Intelligence Test, Second Edition. In
795 *Encyclopedia of Special Education*. <https://doi.org/10.1002/9781118660584.esel325>
- 796 Kaushanskaya, M., & Marian, V. (2009). The bilingual advantage in novel word learning.
797 *Psychonomic Bulletin and Review*, 16(4), 705–710. <https://doi.org/10.3758/PBR.16.4.705>
- 798 Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy:
799 Evidence for a domain general learning mechanism. *Cognition*, 83(2), 35–42.
800 [https://doi.org/10.1016/S0010-0277\(02\)00004-5](https://doi.org/10.1016/S0010-0277(02)00004-5)

- 801 Lemhöfer, K., & Broersma, M. (2012). Introducing LexTALE: A quick and valid Lexical Test
802 for Advanced Learners of English. *Behavior Research Methods*, 44(2), 325–343.
803 <https://doi.org/10.3758/s13428-011-0146-0>
- 804 Love, J., Selker, R., Marsman, M., Jamil, T., Dropmann, D., Verhagen, J., Ly, A., Gronau, Q. F.,
805 Šmíra, M., Epskamp, S., Matzke, D., Wild, A., Knight, P., Rouder, J. N., Morey, R. D., &
806 Wagenmakers, E. J. (2019). JASP: Graphical statistical software for common statistical
807 designs. *Journal of Statistical Software*, 88(1), 1–17. <https://doi.org/10.18637/jss.v088.i02>
- 808 Maye, J., Werker, J. F., & Gerken, L. A. (2002). Infant sensitivity to distributional information
809 can affect phonetic discrimination. *Cognition*, 82(3), 101–111.
810 [https://doi.org/10.1016/S0010-0277\(01\)00157-3](https://doi.org/10.1016/S0010-0277(01)00157-3)
- 811 McMurray, B., Aslin, R. N., & Toscano, J. C. (2009). Statistical learning of phonetic categories:
812 Insights from a computational approach. *Developmental Science*, 12(3), 369–378.
813 <https://doi.org/10.1111/j.1467-7687.2009.00822.x>
- 814 Mirman, D. (2017). *Growth Curve Analysis and Visualization Using R*. CRC press.
815 <https://doi.org/10.1201/9781315373218>
- 816 Misyak, J., & Christiansen, M. H. (2007). Extending statistical learning farther and further:
817 Long-distance dependencies, and individual differences in statistical learning and language.
818 *Proceedings of the Annual Meeting of the Cognitive Science Society*, 29(29).
- 819 Onnis, L., Chun, W. E., & Lou-Magnuson, M. (2018). Improved statistical learning abilities in
820 adult bilinguals. *Bilingualism*, 21(2), 427. <https://doi.org/10.1017/S1366728917000529>
- 821 Onnis, L., Frank, S. L., Yun, H., & Lou-Magnuson, M. (2016). Statistical learning bias predicts
822 second-language reading efficiency. *Proceedings of the 38th Annual Meeting of the*
823 *Cognitive Science Society (CogSci 2016)*.

- 824 Onnis, L., & Thiessen, E. (2013). Language experience changes subsequent learning. *Cognition*,
825 126(2), 268–284. <https://doi.org/10.1016/j.cognition.2012.10.008>
- 826 Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., &
827 Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research*
828 *Methods*, 51(1), 195–203. <https://doi.org/10.3758/s13428-018-01193-y>
- 829 Peña, M., Bonatti, L. L., Nespor, M., & Mehler, J. (2002). Signal-driven computations in speech
830 processing. *Science*, 298(5593), 604–607. <https://doi.org/10.1126/science.1072901>
- 831 Perruchet, P., & Pacton, S. (2006). Implicit learning and statistical learning: one phenomenon,
832 two approaches. *Trends in Cognitive Sciences*, 10(5), 233–238.
833 <https://doi.org/10.1016/j.tics.2006.03.006>
- 834 Pineño, O., & Miller, R. R. (2005). Primacy and recency effects in extinction and latent
835 inhibition: A selective review with implications for models of learning. *Behavioural*
836 *Processes*, 69(2), 223–235. <https://doi.org/10.1016/j.beproc.2005.02.006>
- 837 Poepsel, T. J., & Weiss, D. J. (2016). The influence of bilingualism on statistical word learning.
838 *Cognition*, 152, 9–19. <https://doi.org/10.1016/j.cognition.2016.03.001>
- 839 Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. *Wiley*
840 *Interdisciplinary Reviews: Cognitive Science*, 1(6), 906–914. <https://doi.org/10.1002/wcs.78>
- 841 Saffran, J. R. (2003). Statistical language learning: Mechanisms and constraints. *Current*
842 *Directions in Psychological Science*, 12(4), 110–114. [https://doi.org/10.1111/1467-](https://doi.org/10.1111/1467-8721.01243)
843 8721.01243
- 844 Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants.
845 *Science*, 274(5294), 1926–1928. <https://doi.org/10.1126/science.274.5294.1926>
- 846 Saffran, J. R., Johnson, E. K., Aslin, R. N., & Newport, E. L. (1999). Statistical learning of tone

- 847 sequences by human infants and adults. *Cognition*, 70(1), 27–52.
848 [https://doi.org/10.1016/S0010-0277\(98\)00075-4](https://doi.org/10.1016/S0010-0277(98)00075-4)
- 849 Schad, D. J., Vasishth, S., Hohenstein, S., & Kliegl, R. (2020). How to capitalize on a priori
850 contrasts in linear (mixed) models: A tutorial. *Journal of Memory and Language*, 110,
851 104038. <https://doi.org/10.1016/j.jml.2019.104038>
- 852 Siegelman, N., Bogaerts, L., Christiansen, M. H., & Frost, R. (2017). Towards a theory of
853 individual differences in statistical learning. *Philosophical Transactions of the Royal*
854 *Society B: Biological Sciences*, 372(1711), 20160059.
855 <https://doi.org/10.1098/rstb.2016.0059>
- 856 Siegelman, N., & Frost, R. (2015). Statistical learning as an individual ability: Theoretical
857 perspectives and empirical evidence. *Journal of Memory and Language*, 81, 105–120.
858 <https://doi.org/10.1016/j.jml.2015.02.001>
- 859 Smith, L., & Yu, C. (2008). Infants rapidly learn word-referent mappings via cross-situational
860 statistics. *Cognition*, 106(3), 1558–1568. <https://doi.org/10.1016/j.cognition.2007.06.010>
- 861 Thiessen, E. D., & Saffran, J. R. (2003). When Cues Collide: Use of Stress and Statistical Cues
862 to Word Boundaries by 7- to 9-Month-Old Infants. *Developmental Psychology*.
863 <https://doi.org/10.1037/0012-1649.39.4.706>
- 864 van Doorn, J., van den Bergh, D., Böhm, U., Dablander, F., Derks, K., Draws, T., Etz, A., Evans,
865 N. J., Gronau, Q. F., Haaf, J. M., Hinne, M., Kucharský, Š., Ly, A., Marsman, M., Matzke,
866 D., Gupta, A. R. K. N., Sarafoglou, A., Stefan, A., Voelkel, J. G., & Wagenmakers, E. J.
867 (2020). The JASP guidelines for conducting and reporting a Bayesian analysis.
868 *Psychonomic Bulletin and Review*, 1–14. <https://doi.org/10.3758/s13423-020-01798-5>
- 869 Wagenmakers, E. J. (2007). A practical solution to the pervasive problems of p values.

- 870 *Psychonomic Bulletin and Review*, 14(5), 779–804. <https://doi.org/10.3758/BF03194105>
- 871 Wang, T., & Saffran, J. R. (2014). Statistical learning of a tonal language: The influence of
- 872 bilingualism and previous linguistic experience. *Frontiers in Psychology*, 5, 953.
- 873 <https://doi.org/10.3389/fpsyg.2014.00953>
- 874 Yu, C., & Smith, L. B. (2007). Rapid word learning under uncertainty via cross-situational
- 875 statistics. *Psychological Science*, 18(5), 414–420. [https://doi.org/10.1111/j.1467-](https://doi.org/10.1111/j.1467-9280.2007.01915.x)
- 876 9280.2007.01915.x
- 877

Appendix A

Linguistic profile and contrasts per group in Experiment 1

	Spanish Monolinguals		Spanish-Basque Bilinguals		Spanish-English Bilinguals		ANOVA			Helmert contrasts p-value	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	$F_{(2, 114)}$	<i>p</i>	BF_{10}	MONO-BIL	SPBQ-SPEN
Age	21.8	2.6	21.2	1.9	20.9	2.3	1.610	0.204	0.303	0.088	0.586
Non-verbal IQ	101.5	8.3	100.7	8.6	99.8	6.6	0.481	0.619	0.120	0.406	0.592
Age of Acquisition L1 ^a	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Total Exposure L1 (%)	91.4	8.1	60.3	11.8	64.5	9.9	111.685	< 0.001	> 100	< 0.001	0.070
Self-rated proficiency L1 (1-10)	9.8	0.4	9.8	0.2	9.9	0.3	0.876	0.419	0.166	0.411	0.294
BEST L1 (0-65)	64.6	0.6	64.6	0.7	64.8	0.5	1.425	0.245	0.260	0.217	0.243
Age of Acquisition L2	5.3	1.8	3.0	1.6	3.5	1.7	20.508	< 0.001	> 100	< 0.001	0.237
Total Exposure L2 (%)	7.7	7.2	32.5	13.1	33.5	9.4	80.766	< 0.001	> 100	< 0.001	0.664
Self-rated proficiency L2 (1-10)	4.3	1.8	8.6	0.7	8.1	0.8	149.854	< 0.001	> 100	< 0.001	0.074
BEST L2 (0-65)	25.9	8.2	55.9	6.9	55.9	4.2	264.291	< 0.001	> 100	< 0.001	0.991
LexTALE L1 (%)	-	-	92.9	5.6	93.8	6.3	-	-	-	-	0.506 ^b
LexTALE L2 (%)	-	-	90.7	6.1	88.8	6.0	-	-	-	-	0.176 ^b

Note. Significant contrast terms are highlighted in bold. SD = standard deviation; MONO = Spanish monolinguals; BIL = bilinguals; SPEN = Spanish-English bilinguals; SPBQ = Spanish-Basque bilinguals.

^a Statistic and *p*-value undefined due to zero variance.

^b Difference calculated using Welch t-tests.

Appendix B

Linguistic profile and contrasts per group in Experiment 2

	Spanish Monolinguals (n=40)		Spanish-Basque Bilinguals (n=40)		Spanish-English Bilinguals (n=40)		ANOVA		Helmert contrasts p-value		
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	$F_{(2, 114)}$	<i>p</i>	BF ₁₀	MONO-BIL	SPBQ-SPEN
Age	21.7	2.4	21.8	2.2	21.0	2.4	1.405	0.250	0.252	0.478	0.132
Non-verbal IQ	99.8	6.6	101.1	8.8	100.1	6.6	0.320	0.727	0.103	0.578	0.567
Age of Acquisition L1 ^a	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Total Exposure L1 (%)	91.4	8.6	61.3	8.1	64.8	9.9	136.974	< 0.001	> 100	< 0.001	0.081
Self-rated proficiency L1 (1-10)	9.9	0.3	9.8	0.4	9.9	0.3	1.084	0.342	0.194	0.925	0.144
BEST L1 (0-65)	64.7	0.6	64.6	0.7	64.8	0.4	1.784	0.172	0.344	0.829	0.063
Age of Acquisition L2	5.6	1.5	3.8	1.0	3.5	1.7	25.839	< 0.001	> 100	< 0.001	0.435
Total Exposure L2 (%)	8.6	8.6	34.0	9.6	33.4	9.3	99.097	< 0.001	> 100	< 0.001	0.762
Self-rated proficiency L2 (1-10)	4.2	1.7	8.5	1.0	8.1	0.8	146.243	< 0.001	> 100	< 0.001	0.145
BEST L2 (0-65)	25.6	9.6	56.3	6.5	55.9	4.3	243.908	< 0.001	> 100	< 0.001	0.802
LexTALE L1 (%)	-	-	93.4	5.6	93.3	6.8	-	-	-	-	0.986 ^b
LexTALE L2 (%)	-	-	87.1	7.9	88.9	6.0	-	-	-	-	0.262 ^b

Note. Significant contrast terms are highlighted in bold. SD = standard deviation; MONO = Spanish monolinguals; BIL = bilinguals; SPEN = Spanish-English bilinguals; SPBQ = Spanish-Basque bilinguals.

^a Statistic and *p*-value undefined due to zero variance.

^b Difference calculated using Welch t-tests.

Appendix C

Linguistic profile and contrasts per group in Experiment 3

	Spanish Monolinguals (n=40)		Spanish-Basque Bilinguals (n=40)		Spanish-English Bilinguals (n=37)		ANOVA			Helmert contrasts p-value	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	$F_{(2, 114)}$	<i>p</i>	BF_{10}	MONO-BIL	SPBQ-SPEN
Age	21.7	2.5	21.9	1.9	21.0	2.4	1.712	0.185	0.328	0.696	0.072
Non-verbal IQ	102.2	8.0	101.5	6.2	100.6	6.5	0.477	0.622	0.120	0.313	0.583
Age of Acquisition L1 ^a	0.0	0.0	0.0	0.0	0.0	0.0	-	-	-	-	-
Total Exposure L1 (%)	90.7	7.5	62.5	10.8	65.0	9.4	111.191	< 0.001	> 100	< 0.001	0.242
Self-rated proficiency L1 (1-10)	9.9	0.3	9.8	0.3	9.9	0.2	1.54	0.219	0.286	0.962	0.082
BEST L1 (0-65)	64.7	0.5	64.7	0.5	64.8	0.4	1.618	0.203	0.304	0.145	0.284
Age of Acquisition L2	5.5	2.0	2.9	1.0	3.6	1.7	26.798	< 0.001	> 100	< 0.001	0.067
Total Exposure L2 (%)	8.9	7.2	30.5	9.3	33.1	8.9	95.487	< 0.001	> 100	< 0.001	0.183
Self-rated proficiency L2 (1-10)	3.9	1.6	8.5	0.9	8.1	0.9	180.184	< 0.001	> 100	< 0.001	0.082
BEST L2 (0-65)	26.9	9.2	56.2	7.3	55.7	4.3	210.094	< 0.001	> 100	< 0.001	0.766
LexTALE L1 (%)	-	-	91.1	7.6	93.9	5.9	-	-	-	-	0.077 ^b
LexTALE L2 (%)	-	-	88.7	8.9	88.9	6.1	-	-	-	-	0.900 ^b

Note. Significant contrast terms are highlighted in bold. SD = standard deviation; MONO = Spanish monolinguals; BIL = bilinguals; SPEN = Spanish-English bilinguals; SPBQ = Spanish-Basque bilinguals.

^a Statistic and *p*-value undefined due to zero variance.

^b Difference calculated using Welch t-tests.