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Learning across languages: bilingual experience supports dual language statistical word segmentation

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Abstract

Bilingual acquisition presents learning challenges beyond those found in monolingual environments, including the need to segment speech in two languages. Infants may use statistical cues, such as syllable-level transitional probabilities, to segment words from fluent speech. In the present study we assessed monolingual and bilingual 14-month-olds' abilities to segment two artificial languages using transitional probability cues. In Experiment 1, monolingual infants successfully segmented the speech streams when the languages were presented individually. However, monolinguals did not segment the same language stimuli when they were presented together in interleaved segments, mimicking the language switches inherent to bilingual speech. To assess the effect of real-world bilingual experience on dual language speech segmentation, Experiment 2 tested infants with regular exposure to two languages using the same interleaved language stimuli as Experiment 1. The bilingual infants in Experiment 2 successfully segmented the languages, indicating that early exposure to two languages supports infants' abilities to segment dual language speech using transitional probability cues. These findings support the notion that early bilingual exposure prepares infants to navigate challenging aspects of dual language environments as they begin to acquire two languages.

RESEARCH HIGHLIGHTS

- Bilingual infants statistically segment words when hearing interleaved languages; monolinguals do not.
- Infants show evidence of aggregating statistical regularities across interactions.

1 | INTRODUCTION

To acquire language, learners must navigate intersecting levels of phonological, lexical, and syntactic structure. Given the complexity of the learning problem, it is remarkable that children acquire languages as rapidly as they do. Children in bilingual environments experience demanding learning conditions that go beyond the complexities of acquiring language in monolingual environments (Byers-Heinlein & Fennell, 2014; Costa & Sebastián-Gallés, 2014). Consider the tasks that bilingual infants face in the earliest stages of development. They must discover the presence of multiple linguistic systems and identify reliable cues to distinguish between languages. As they process speech, infants must apply these cues to shift between linguistic contexts in real time. The presence of two languages also provides bilingual infants with noisier input than monolinguals. Languages may have overlapping or conflicting regularities that infants must tease apart to successfully learn each language's unique structure. Furthermore, the divided nature of dual language input means that infants from bilingual environments receive less exposure to each individual language than monolinguals do. Despite these challenges, infants from bilingual environments appear to reach language milestones at a similar pace to monolinguals and have comparable conceptual vocabularies (De Houwer, Bornstein, & Putnick, 2014; Hoff et al., 2012; Pearson, Fernandez, & Oller, 1993). The developmental trajectory of young bilinguals indicates that infants are well equipped to manage the

additional processing that dual language input requires. However, we know relatively little about the mechanisms of early bilingual language acquisition (see Costa & Sebastián-Gallés, 2014, for a recent review).

The present research investigates whether infants can perform a fundamental learning task when faced with dual language input – segmenting words from fluent speech. The ability to detect individual words in continuous speech provides a foundation for emerging lexical and syntactic knowledge (Graf Estes, Evans, Alibali, & Saffran, 2007; Lany & Gómez, 2008). Segmentation is a non-trivial task, as words are typically heard surrounded by other words, with few pauses or other explicit cues to reliably indicate word boundaries (e.g., Aslin, Woodward, LaMendola, & Bever, 1996; but see Brent & Siskind, 2001). However, a number of cues to word boundaries are present in the speech stream and accessible to infant learners. These include prosodic cues, such as lexical stress (e.g., Johnson & Jusczyk, 2001), as well as statistical cues, such as phonotactic and allophonic patterns (e.g., Jusczyk, Hohne, & Bauman, 1999; Mattys & Jusczyk, 2001) and syllable co-occurrences (e.g., Saffran, Aslin, & Newport, 1996). The properties of these cues vary by language due to differences in phoneme categories, phonotactic rules, syllable sets, words, syntax, and rhythmic properties, among many other features. Therefore, it is likely that the utility of different segmentation strategies differs across languages, and that infants' use of these regularities may also vary accordingly (e.g., Nazzi, Iakimova, Bertoncini, Frédonie, & Alcantara, 2006). Thus, the challenge of word segmentation may be amplified in bilingual environments, as dual language learners must index their speech input by language, and inhibit cross-linguistic interference in order to acquire and apply the appropriate segmentation strategies for their languages.

We investigated bilingual word segmentation by examining infants' use of a statistical cue, syllable-level transitional probabilities, to segment speech in two languages. Within the first year of life, infants can use syllable co-occurrence regularities to discover words units, even when other cues are absent (e.g., Aslin, Saffran, & Newport, 1998; Graf Estes, 2012; Saffran et al., 1996). Within a language, syllables that co-occur frequently are likely to form words, whereas syllables that co-occur infrequently are likely to mark word boundaries (Swingley, 2005). Statistical word segmentation based on transitional probabilities may allow infants to detect word forms that can then be linked to meanings (Erickson, Thiessen, & Graf Estes, 2014; Graf Estes et al., 2007; Lany & Saffran, 2010) and to discover language-specific segmentation cues, such as lexical stress (Erickson & Thiessen, 2015; but see Johnson & Jusczyk, 2001). Thus, bilinguals may use transitional probability information early in development to support the acquisition of language-specific patterns in each of their native languages. However, tracking transitional probabilities in two languages also presents challenges. Because languages have different vocabularies and different phonological patterns, syllable transitional probabilities are likely to diverge. Therefore, it may be important for bilingual infants to be able to track these patterns separately across languages, to avoid the accumulation of statistical noise that would derail word segmentation.

It is possible that infants have the capacity to track syllable probabilities in multiple languages regardless of their language experience. From a very young age, infants can learn patterns of syllable co-occurrences with only a few minutes of listening time (Johnson & Tyler, 2010; Saffran et al., 1996; Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009). Infants can also rapidly learn complex, multi-level patterns in a novel language, as demonstrated by their ability to use syllable co-occurrences to discover individual word forms and the grammatical rules that govern their combination (Saffran & Wilson, 2003; see also Lany & Gomez, 2008). These feats of learning have revealed monolingual infants' robust abilities to track statistical regularities within a single language. However, we do not yet have evidence to confirm whether infants can track interleaved systems of probabilities during word segmentation.

Work by Weiss, Gerfen, and Mitchel (2009) supports the notion that monolingual adults can track statistical regularities in dual language environments. Weiss and colleagues presented adults with two artificial languages that contained transitional probability cues to word boundaries. They found that participants segmented words from the languages. This was true even when the two languages overlapped at the syllable level, which would introduce conflicting transitional probabilities if the languages were not processed separately. Participants successfully navigated the simulated bilingual environment in the absence of significant prior experience with multiple languages. This indicates that bilingual experience is not requisite for adults to accurately track statistical regularities for two languages. However, it is unclear whether the same is true of infants, who have reduced cognitive capacity relative to adults (e.g., working memory, inhibitory control; Diamond, 2013).

Early bilingual experience may prepare infants for dual language statistical learning. Bilingual learners must distinguish between multiple, unique linguistic systems present in one environment (e.g., Byers-Heinlein & Werker, 2009). In infancy, bilinguals are attuned to auditory and visual cues for discriminating between languages (Bosch & Sebastián-Gallés, 2001; Byers-Heinlein, Burns, & Werker, 2010; Sebastián-Gallés, Albareda-Castellot, Weikum, & Werker, 2012; Weikum et al., 2007). Experience discovering and applying cues that help index languages may facilitate later steps in bilingual acquisition by preparing infants to track language changes in their speech input.

In addition, a nascent literature examining bilingual cognitive development in infancy suggests that bilinguals may differ from monolingual infants in some aspects of information processing. This research has revealed that bilingual experience is associated with positive outcomes for inhibitory control (Kovács & Mehler, 2009a, 2009b; Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011), information encoding (Singh et al., 2015), and memory generalization (Brito & Barr, 2012, 2014). For example, Kovács and Mehler (2009a) found that 7-month-old infants from bilingual homes were more effective than monolinguals at inhibiting a previously learned response to visual stimuli. Similarly, Singh and colleagues (2015) found that 6-month-old bilinguals encoded visual information more efficiently than same-age monolinguals in a habituation paradigm. These findings suggest that within the first year of life, experience with two languages affects how infants process input from the world around them. In turn, cognitive effects like these could facilitate infants' acquisition of two languages.

At present, the literature examining bilingual cognition in infancy is limited. Further work is needed to verify the cognitive consequences of processing bilingual input, to assess whether these outcomes generalize to diverse bilingual populations, and to determine the sources of any differences. However, there is additional evidence of positive cognitive correlates of bilingual experience in research with school-aged and adult bilinguals (see Akhtar & Menjivar, 2012; Bialystok, 2010, for reviews; but also see Paap, Johnson, & Sawi, 2015, for contrasting findings). Across a number of studies, bilinguals have been more successful than monolinguals in tasks requiring participants to employ inhibitory control by suppressing a pre-potent response (e.g., Bialystok, Craik, Klein, & Viswanathan, 2004; Carlson & Meltzoff, 2008; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; see Adesope, Lavin, Thompson, & Ungerleider, 2010, for a systematic review). The difference between monolinguals' and bilinguals' use of inhibitory control in these tasks is thought to be a consequence of frequently suppressing a dominant language during production of a second language (Bialystok et al., 2004; Emmorey, Luk, Pyers, & Bialystok, 2008). However, the inhibitory control benefit found for preverbal infants from bilingual homes (Kovács & Mehler, 2009a) suggests that the difference may not be the result of practiced inhibition during language production alone. Early cognitive outcomes for bilinguals may be influenced by the application of attentional resources for processing interleaved language systems. For example, infants must manage attention to identify reliable cues that distinguish between languages (e.g., phonological patterns, speaker identity, etc.), actively monitor speech input for language changes, and inhibit activation of information from the opposing language during speech processing. This effort may sculpt the developing brain, in turn improving bilingual infants' abilities to acquire and process their two languages. If this were true, we would expect cognitive consequences of bilingualism to appear before infants are fluent in either language, and for the changes to be relevant for surmounting challenging aspects of the bilingual experience in infancy, such as word segmentation.

In summary, it is possible that monolingual infants' statistical learning abilities would allow them to track syllable co-occurrence regularities across multiple languages. However, we predicted that bilingual experience would facilitate statistical learning in dual language environments. Infants from bilingual homes have experience applying the skills necessary to shift between language contexts and to acquire two distinct language structures. In addition, domain-general cognitive sequelae of early bilingualism may reduce the cognitive load of processing two languages by increasing the efficiency of information encoding (e.g., Singh et al., 2015), or enhancing infants' abilities to employ inhibitory control as language contexts change (e.g., Kovács & Mehler, 2009a, 2009b). To test infants' statistical learning of dual speech streams, the present study examined monolingual and bilingual infants' abilities to segment speech from two interleaved artificial languages using syllable transitional probabilities. We tested 14-month-old infants, an older age than in many prior statistical learning tasks (e.g., 8-month-olds; Aslin et al., 1998; Pelucchi, Hay, & Saffran, 2009; Saffran et al., 1996), because bilingual infants begin to develop lexicons in both languages around this age (e.g., De Houwer et al., 2014).

Experiment 1 tested monolingual infants. In Experiment 1A, we presented infants with one of two artificial languages to establish a baseline learning pattern for infants listening to an individual artificial language. After the language exposure, we assessed their recognition of words previously heard in the speech using a listening preference procedure (e.g., Cooper & Aslin, 1990). We hypothesized that monolinguals would successfully use transitional probabilities to segment an individual artificial language, similar to past work (e.g., Aslin et al., 1998; Graf Estes, 2012; Saffran et al., 1996). Experiment 1B assessed infants' preferences for the same test items without prior exposure to the artificial language, to confirm that performance in Experiment 1A was driven by the language exposure rather than intrinsic test item preferences. In Experiment 1C, monolingual infants heard the same languages that were used in Experiment 1A, but the languages were presented in eight interleaved segments (e.g., L1, L2, L1, L2 …). Thus, Experiment 1C investigated whether monolingual infants' statistical learning abilities are robust in the face of bilingual input. We predicted that tracking interleaved sets of syllable co-occurrence regularities would prove too taxing for infants without regular experience navigating two languages.

In Experiment 2, we tested infants with at-home bilingual experience in an identical procedure to Experiment 1C. Therefore, Experiment 2 assessed the influence of early bilingual experience on infants' statistical segmentation in a task that simulates a key challenge of bilingual environments – learning the structures of two interleaved speech streams. We expected bilinguals in Experiment 2 to learn the structure of the interleaved languages and to subsequently recognize syllable sequences that had formed words in the speech stream. We hypothesized that early exposure to multiple languages would provide infants with the experience necessary to track statistical regularities within multiple novel languages.

2 | EXPERIMENT 1A

Experiment 1A examined monolingual infants' abilities to use transitional probability cues to segment one individually presented artificial language. Infants heard an artificial language and were subsequently tested on their listening preferences for syllable sequences with different statistical properties in the language (i.e., sequences that formed words vs. sequences that did not). This experiment provided a baseline learning pattern. Identical artificial language stimuli and test items were then used in the subsequent interleaved-language segmentation tasks (Experiments 1C and 2).

2.1 | Method

2.1.1 | Participants

Twenty-four 14-month-old (M = 14.20 months; range = 13 months, 22 days–14 months, 29 days; male = 12) monolingual infants participated in Experiment 1A. Infants in all experiments met the following criteria: they were born full-term, had no known vision or hearing

impairments, and no history of chronic ear infections. All infants were from Northern California. Monolingual infants were from English-speaking homes. According to parental report, six infants had minimal exposure to an additional language or languages comprising up to 5% of their overall language input. Household income was estimated from census survey data (US Census Bureau), based on participants' home ZIP codes (see Byers-Heinlein, Fennell, & Werker, 2013, for a similar income estimation method) and parents reported their level of education. The mean estimated household income was $88,926 (range = $51,261–$119,937; one family not reporting), and the mean level of education for both mothers and fathers corresponded to 'Some college'. For all experiments, the education level range was 'High school diploma' – 'Doctoral degree.' An additional eight infants were excluded from the final analyses because of fussiness or crying. One additional infant was identified as an outlier during preliminary analysis (listening time difference to words – part-words greater than 2*SD* from the group mean), and was excluded from the final sample.

2.1.2 | Stimuli

Artificial languages

Infants were exposed to one of two artificial languages (L1 or L2), each consisting of four disyllabic (CVCV) nonce words (see Table 1) concatenated to form a fluent speech stream without pauses or other acoustic cues to word boundaries. Each word was repeated 120 times. The syllable-to-syllable transitional probabilities within words were all 1.0 (e.g., *ti* was always followed by *may*) and the probabilities across words ranged from 0 to .33. Within and across languages, no syllable occurred in more than one word. The words were concatenated in a randomized order, with the exception that no word occurred twice in succession. A male speaker recorded monotone syllable sequences for L1 and a female speaker recorded syllables for L2. The median pitch of each syllable recording was standardized to 115 Hz for L1 (male voice) and 200 Hz for L2 (female voice) using Praat audio analysis and editing software (Boersma & Weenink, 2012). Volume of the stimuli was set to 65 dB, as measured with a decibel meter from the approximate location of a participant's head.

In order to reduce the likelihood of unintentional pitch, syllable length, or other acoustic cues to word boundaries, while still maintaining appropriate co-articulation, each speaker recorded all possible three-syllable sequences within each language. The middle syllable of each triplet was extracted and reassembled in the appropriate contexts using Praat. For example, the tri-syllabic contexts bu|**ti**|may, ti|**may**|pi, may|**pi**|mo, and pi|**mo**|ku were used to create the two-word sequence in L1, ***timay***|***pimo*** (with ***dobu*** proceeding and ***kuga*** following). This formed 4 min, 50 sec of fluent speech in each language.

Each artificial language recording was divided into four segments, so that identical language stimuli could be presented (interleaved) in Experiments 1C and 2. Five seconds of silence separated each speech interval. To prevent utterance edges from acting as segmentation cues, half of the intervals began at word onsets and half began with the second syllable of a word, with the constraint that the test items did not begin or end intervals. These constraints determined the length of each interval (L1 [sec]: 64.5, 79.9, 81.0, 64.6; L2 [sec]: 64.6, 79.7, 80.9, 64.7). Infants were randomly assigned to listen to exposure and test stimuli from either L1 or L2.

TABLE 1 Artificial language words and part-words from Experiments 1 and 2

Language	Words	Part-words
L1	***timay***, ***dobu***, *kuga*, *pimo*	***gado***, ***moti***
L2	***rayki***, ***musa***, *taino*, *lasai*	***noray***, ***sala***

Note. Test items are listed in bold.

Test items

Infants were tested using a preferential listening procedure designed to compare their attention to word and part-word test items from either L1 or L2. Word test items were syllable sequences that co-occurred consistently, forming two of the words that were present in the artificial language (e.g., *timay* in L1; see Table 1). Part-word test items were syllable sequences formed from the offset syllable of one word and onset syllable of another word within the language. Part-word syllable sequences occurred across word boundaries in the language, but did not co-occur consistently (e.g., the part-word syllable sequence *moti* was formed when the L1 word *pimo* preceded *timay*, although *pimo* was also followed by other L1 words, making *moti* a low probability sequence). Based on similar experiments, we predicted that if infants segmented the words during the exposure period, they should listen longer to the part-words than to the words from the languages (e.g., Aslin et al., 1998; Johnson & Tyler, 2010; Saffran et al., 1996).

Test items were created by splicing appropriate onset and offset syllables from the tri-syllabic recordings described above. Repetitions of the test items were separated by 800 ms of silence. There were 16 test trials (two distinct word and two distinct part-word test items per block, four repetitions each). The presentation of trials was randomized by block. Each infant heard test items from the language (L1 or L2) that they had listened to during the exposure period.

To create the audio-visual stimuli for the listening preference test, the auditory test items were each paired with an identical animation of an orange petal continuously rotating in a circle. Infants' attention to the audio-visual stimuli was used to measure their listening preference for the word versus part-word test items.

2.1.3 | Procedure

Infants were exposed to either L1 or L2 in a sound-attenuated booth during quiet play with a parent. Parents were instructed not to talk during the experiment. The exposure period lasted 5 min, 5 sec. This exposure duration was longer than in many previous statistical word segmentation tasks (e.g., 2 minutes; Aslin et al., 1998; Johnson & Jusczyk, 2001; Saffran et al., 1996; but see Graf Estes & Lew-Williams, 2015; Saffran et al., 2008, for long exposure periods). The extended

exposure was designed to support learning in Experiments 1C and 2, in which infants had the added challenge of segmenting interleaved languages. After the exposure period, the infant and parent moved to a separate test booth and the parent was reminded not to speak or direct the child's attention by pointing.

During testing, stimuli were presented on a large television with integrated speakers approximately 1 m in front of the infant, who was seated on a parent's lap. Parents wore headphones, which played masking music to prevent them from unintentionally biasing their infants' looking behavior. Before the first test trial, infants heard an additional 30-sec 'refresher' of the test language accompanied by an animated video. The refresher stimulus was intended to bridge the delay between exposure and test.

Habit X software (Cohen, Atkinson, & Chaput, 2004) was used to present stimuli and record infant looking time. Infants were tested on word and part-word test items from the language they had listened to during the exposure period (L1 or L2). The experimenter viewed the infant from a separate control booth and was blind to trial type. Each trial began with an animated video to capture the infant's attention. The experimenter presented a test item when the infant looked at the screen, and ended the presentation when the infant looked away for more than 1 sec. Infants first viewed a familiarization trial in which the visual animation (rotating orange petal) appeared, accompanied by an attention-getting phrase in English. This trial was included to prevent inflated attention during the first word or part-word test trial. Each test trial consisted of repetitions of an isolated word or part-word recording paired with the orange petal video, described above.

2.2 | Results and discussion

Preliminary analyses of listening time discrimination scores (listening to words − part-words) revealed no differences in infant performance based on gender, $t(22) = -.65$, $p = .52$, or test language (L1 versus L2, see Table 2), $t(22) = -1.81$, $p = .09$. Therefore, the subsequent analysis collapsed across these variables. We conducted a two-tailed, paired-samples *t*-test to determine whether infants' mean listening time differed across trials in which infants heard words versus part-word test items. As shown in Figure 1, infants listened significantly longer to the part-words, $t(23) = 3.47$, $p = .002$, $d_z = 0.71$.

TABLE 2 Mean listening time discrimination scores (words − part-words) by language in sec

Experiment	Test language	Mean discrimination score (*SD*)
1A	L1	−1.82 (1.59)
	L2	−0.61 (1.68)
1B	L1	−0.46 (2.38)
	L2	0.49 (1.74)
1C	L1	−0.42 (1.29)
	L2	−0.27 (2.02)
2	L1	−0.80 (2.27)
	L2	−0.92 (1.89)

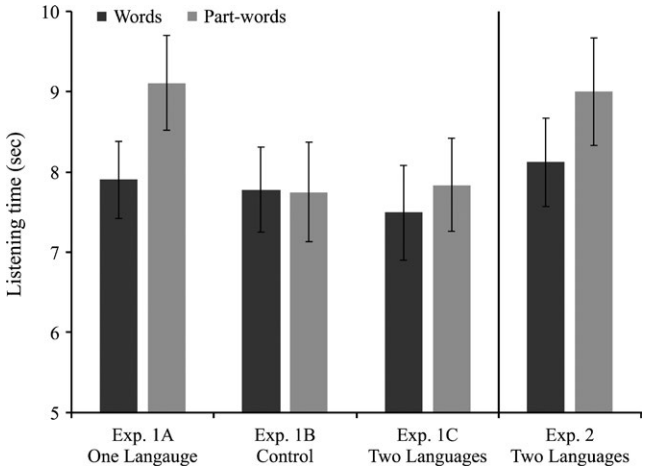

FIGURE 1 Infants' mean listening time to word and part-word test trials in Experiment 1 (monolinguals) and Experiment 2 (bilinguals). Error bars represent standard errors.

The results from Experiment 1A suggest that monolingual infants successfully segmented the artificial languages after a brief exposure to a single language. They demonstrated a listening-time preference for part-words over words, similar to previous work using this method (e.g., Aslin et al., 1998; Johnson & Tyler, 2010; Saffran et al., 1996).

3 | EXPERIMENT 1B

Experiment 1B presented a control task designed to confirm that infants' listening times to test items in Experiment 1A were driven by experience with the artificial language stimuli rather than inherent test item preferences. Infants completed the listening preference task only, with no prior artificial language exposure.

3.1 | Method

3.1.1 | Participants

Twenty-three 14-month-old (*M* = 14.33 months; range = 13 months, 20 days–14 months, 30 days; male = 11) monolingual infants participated. They met the same inclusion criteria as Experiment 1A. All infants were from English-speaking homes. According to parental report, two infants had minimal exposure to an additional language (up to 5% of overall language input). The mean estimated household income was $83,326 (range = $59,578–$119,937; two families not reporting), and the mean level of education for mothers and fathers corresponded to 'Some college' (one family not reporting). Thirteen additional infants were excluded from the final analyses due to fussiness or crying (7), equipment error (3), experimenter error (2), child covering eyes (1). One additional infant was identified as an outlier using the same criteria as Experiment 1A, and was excluded from the final sample.

3.1.2 | Stimuli and procedure

Infants were randomly assigned to hear test items from L1 or L2. The testing procedures were identical to Experiment 1A. However, infants in this experiment were not exposed to artificial language stimuli prior to testing.

3.2 | Results and discussion

Preliminary analyses revealed no differences in listening time discrimination scores (words − part-words) based on gender, $t(21) = -1.01$, $p = .33$, or test language (L1 versus L2, see Table 2), $t(21) = -1.12$, $p = .28$. The subsequent analysis collapsed across these variables. A two-tailed, paired-samples *t*-test indicated that infants did not discriminate words from part-words at test, $t(22) = 0.08$, $p = .94$, $d_z = .01$, when they had no prior exposure to an artificial language. This finding demonstrates that infants' preferences after the language exposure were driven by experience with the artificial language stimuli.

4 | EXPERIMENT 1C

To assess monolinguals' abilities to segment dual language streams using syllable co-occurrence regularities, we presented infants with the two artificial languages in interleaved segments (e.g., L1, L2, L1, L2…). It is possible that monolingual infants' abilities to segment languages individually would allow them to segment the languages when presented together. However, it is also possible that monolinguals do not possess the necessary skill set to track probability patterns for multiple languages, limiting their abilities to segment the speech.

4.1 | Method

4.1.1 | Participants

Twenty-three 14-month-old (M = 14.45 months; range = 13 months, 20 days–14 months, 29 days; male = 13) monolingual infants participated in the present study. Infants met the same inclusion criteria as Experiment 1A. One infant was exposed to Spanish for approximately 2.5% of her overall language input. The mean estimated household income was $83,956 (range = $58,746–$112,862; two families not reporting). The reported mean level of education for mothers corresponded to '4-year degree from a college/trade school', and 'Some college' for fathers. Nine additional infants were excluded from the final analyses due to fussiness or crying (5), parent interference (2), child covering eyes (1), equipment error (1). One additional infant was identified as an outlier using the same criteria as Experiment 1A, and was also excluded from the final analyses.

4.1.2 | Stimuli

Infants were exposed to two artificial languages (L1 and L2), identical to those used in Experiment 1A (see Table 1). However, unlike in Experiment 1A, each infant was exposed to both artificial languages. The four L1 and four L2 segments were interleaved, alternating between the two languages to form eight intervals. As in Experiment 1A, there were 5 sec of silence between each interval.

Although infants heard both languages, they were only tested on one of the two artificial languages; half of the infants heard test items from L1 and half heard items from L2. This allowed us to use a test procedure and test items identical to Experiment 1A, in which there were 16 test trials (two words, two part-words; four trials each; all presented in the same voice). The L1 and L2 test items were identical to those used in Experiment 1A. Thus, any performance differences between experiments were due to the language exposure, rather than the test procedure.

4.1.3 | Procedure

Infants were exposed to the interleaved language stimuli in a sound-attenuated booth during quiet play with a parent. The exposure period lasted 10 min, 15 sec. Infants listened to each of the two languages for the same amount of time as infants in Experiment 1A (i.e., approximately 5 minutes per language). After the exposure period, infants heard an additional 30-sec refresher of each language accompanied by an animated video. The presentation order of the two refresher segments was randomized. After the refresher video, infants completed a testing procedure identical to Experiment 1A with one of the two artificial languages.

4.2 | Results and discussion

Preliminary analyses of listening time discrimination scores (words − part-words) revealed no differences in infant performance based on gender, $t(21) = -0.69$, $p = .50$, test language (L1 versus L2, see Table 2), $t(21) = -0.21$, $p = .83$, or refresher language presentation order, $t(21) = -0.75$, $p = .46$, so the subsequent analysis collapsed across these variables. A two-tailed, paired-samples *t*-test revealed that listening times to word and part-word test trials were not significantly different, $t(22) = 1.03$, $p = .32$, $d_z = 0.21$. Monolingual infants did not reliably discriminate between word and part-word test items (see Figure 1).

The present pattern of results suggests that monolinguals did not segment the artificial language stimuli based on transitional probabilities present in the speech when the languages were interleaved. Monolingual infants in Experiment 1A discriminated between identical test items after hearing just one of the languages. It is not yet clear what prevented the monolingual infants from learning the interleaved languages. Difficulty tracking separate syllable patterns for the languages may have contributed. While prior work with monolinguals has shown that, from birth, infants are able to distinguish between two languages when they come from distinct rhythmic classes (Nazzi, Bertoncini, & Mehler, 1998), the languages in the present experiment had similar rhythmic patterns (monotone, 2-syllable words). In addition, speaker gender may not have been a sufficiently strong categorization cue to allow monolingual infants to index the input by language. However,

work by Weiss and colleagues (2009) found that monolingual adults presented with two interleaved artificial languages could successfully segment the speech using transitional probability cues. It is possible that in Weiss et al.'s (2009) research, adults' greater cognitive capacity (e.g., inhibitory control, working memory; Diamond, 2013) allowed them to succeed, whereas infants may lack the necessary information-processing resources to support segmentation in the task.

Prior bilingual experience may support infants' abilities to statistically segment dual language input. Early experience navigating two languages has been found to affect cognitive systems (e.g., inhibitory control, Kovács & Mehler, 2009a, 2009b; information encoding, Singh et al., 2015) that could support infants' abilities to segment speech from two languages. In addition, experiences specific to bilingual environments, such as the need to identify cues that distinguish between languages and to monitor speech input for language changes, may allow bilinguals to succeed in this segmentation task. Therefore, in Experiment 2 we investigated whether prior, real-world bilingual experience would affect infants' segmentation abilities in this dual language task.

5 | EXPERIMENT 2

Experiment 2 examined bilingual infants' performance in a statistical word segmentation task identical to the task completed by monolingual infants in Experiment 1C. We predicted that bilingual experience would influence infants' abilities to segment dual speech streams using transitional probability cues.

5.1 | Method

5.1.1 | Participants

Twenty-three 14-month-old (M = 14.30; range = 13 months, 14 days–15 months, 0 days; male = 14) bilingual infants participated in the study. Infants were regularly exposed to English and a second language comprising 25% to 75% of their total language input (M = 51%; range = 26%–73%). Bilingual status was determined using a structured parent interview, in which parents reported the individuals who interacted with the infant, the languages spoken by those individuals, and the proportion of time individuals used each language in the presence of the infant. From this, we determined the languages each infant had regular exposure to, and calculated the percent of time infants were exposed to each of these languages. The following second languages were represented: Spanish (11), Vietnamese (4), Hmong (2), Mandarin (2), Laotian (1), Portuguese (1), Russian (1), and Tagalog (1). Infants had been exposed to both languages from birth. One infant had significant exposure to a third language as well (>10% of her overall language exposure). The pattern of results did not change with this infant excluded. Infants were tested in the same location and met the same inclusion criteria as Experiment 1. The mean estimated household income was $83,544 (range = $48,898–$110,615), and the mean level of education corresponded to '4-year degree from a college/trade school' for mothers and 'Some college' for fathers (one family not reporting). Estimated household income did not differ between monolinguals in Experiment 1C and bilinguals in Experiment 2, $t(42) = -.07$, $p = .94$, $d = .02$. An additional nine infants were excluded from the final analyses due to fussiness or crying (6), parent interference (1), equipment error (1), experimenter error (1). One additional infant was identified as an outlier using the same criteria as Experiment 1, and was excluded from the final analyses.

5.1.2 | Stimuli and procedure

Stimuli and procedures were identical to Experiment 1C, described above.

5.2 | Results and discussion

Preliminary analyses revealed no differences in listening time discrimination scores based on gender, $t(21) = 0.66$, $p = .51$, refresher language presentation order, $t(21) = -0.44$, $p = .67$, or test language (L1 versus L2, see Table 2), $t(21) = 0.14$, $p = .89$, so the subsequent analysis collapsed across these variables. A two-tailed, paired-samples t-test revealed that bilingual infants listened longer to part-word test items than word test items, $t(22) = 2.08$, $p = .050$ $d_z = 0.43$ (see Figure 1). This preference pattern parallels the monolinguals' pattern in Experiment 1A and prior investigations of statistical word segmentation (e.g., Aslin et al., 1998; Johnson & Tyler, 2010; Saffran et al., 1996). This indicates that bilinguals, who had real-world experience navigating dual language environments, successfully segmented the interleaved speech.

6 | GENERAL DISCUSSION

The present research investigated monolingual and bilingual infants' abilities to learn by tracking statistical regularities in interleaved streams of linguistic input. In Experiment 1, when monolingual infants heard two artificial languages in interleaved segments, they did not display evidence of learning the languages' syllable patterns. Monolingual infants were able to learn the same syllable patterns when listening to just one of the languages. The interleaved exposure was designed to mimic a demand of natural bilingual environments, namely learning from input that switches between two languages. In Experiment 2, bilingual infants were able to learn the structure of the interleaved speech streams under conditions that were identical to those in which monolinguals failed to learn. Our findings suggest that infants can learn statistical patterns for interleaved input streams when they have related experience in their native languages.

To learn from the interleaved languages, infants had to maintain information about each artificial language while listening to speech from the opposing language. This indicates that infants are able to retain statistical information across time, at least briefly, while processing other speech input. The ability to maintain speech information and integrate learning across interactions is important for any language

learner, but may be particularly challenging in bilingual environments. For bilinguals, conversations and interactions shift between languages; therefore, the ability to retain and synthesize information across multiple interactions within a particular language is crucial.

The present study is the first, to our knowledge, to demonstrate that infants learning two languages employ statistical learning mechanisms to segment words in fluent speech, as found with monolinguals in past research (e.g., Saffran et al., 1996). This suggests that bilinguals and monolinguals can employ similar learning strategies to process speech, despite inherent differences in their language environments (Poepsel & Weiss, 2016; Yim & Rudoy, 2013). In addition, this work is the first to show that statistical learning may be a viable tool for infants to segment dual speech streams. Early application of the ability to track interleaved systems of syllable patterns may allow bilinguals to detect words in each language and to discern additional language-specific segmentation strategies. In turn, these strategies could help bilinguals' vocabularies grow at a similar pace to monolinguals, despite divided language input (e.g., De Houwer et al., 2014; Hoff et al., 2012; Pearson et al., 1993).

This study builds on past research suggesting that bilingual and monolingual infants differ in aspects of information processing. Research with adult bilinguals has shown that fluency in two or more languages may enhance the ability to deploy attention and suppress context-irrelevant information, particularly when the languages were learned in childhood (Adesope et al., 2010; Bialystok, 2010). Evidence of similar inhibitory control outcomes have been reported for bilingual infants and toddlers as well (Kovács & Mehler, 2009a, 2009b; Poulin-Dubois et al., 2011). Recent work has also identified positive effects of bilingualism for other aspects of cognition, such as information encoding (Singh et al., 2015) and memory generalization (Brito & Barr, 2012, 2014) for bilinguals as young as 6 months of age. The present study provides further evidence that early experience navigating bilingual environments influences how infants process perceptual input, and tunes learning mechanisms to meet the challenges of acquiring two languages.

There are a number of potential explanations for bilingual infants' success in the dual language segmentation task. One possibility is that early bilingual experience affects infants' statistical learning abilities in general, allowing them to track probabilistic patterns more efficiently than monolinguals, regardless of the number of input streams present. However, previous work with older children and adults suggests that monolinguals and bilinguals are similar in their abilities to track patterns in single input streams. For example, Yim and Rudoy (2013) found that monolingual and bilingual children (5- to 13-year-olds) did not differ in their abilities to detect consistently co-occurring elements in streams of shapes or tones. In addition, Poepsel and Weiss (2016) recently found that bilingual adults did not differ from monolinguals in a cross-situational statistical learning task requiring participants to disambiguate word referents within a single-language context. However, bilinguals' performance was better than monolinguals when referents were labeled with two unique words, mimicking the dual input streams present in a bilingual word learning environment. It is still possible that bilinguals can track highly complex statistical patterns (i.e., in languages with large vocabularies or multi-level statistical patterns) more effectively than monolinguals; this remains to be tested. Alternatively, bilingual experience may not directly affect the broad ability to track probabilistic information. Bilingualism may influence other aspects of information processing, which in turn could affect how efficiently young bilinguals learn about statistical regularities in two languages (e.g., Poepsel & Weiss, 2016).

One bilingual experience relevant to the present study is the need to detect cues signaling a shift between languages. Prior experience separating languages may have allowed the bilinguals in Experiment 2 to exploit the indexing cues that were available in the artificial languages. Each language was spoken by a distinct voice (one male, one female), each contained different syllable sets, and the interleaved segments were separated by brief silences. Related research by Gebhart, Aslin, and Newport (2009) has shown that the ability to identify transitions between two speech streams affects learning of that input. Monolingual adults exposed to one artificial language were unable to learn the syllable regularities of a second artificial language presented immediately after the first. Adding a pitch change to cue the transition between languages was not sufficient to improve learning of the second language, but performance improved when the transition was made explicit (i.e., via task instructions and the insertion of a pause between languages). Weiss and colleagues (2009) also found that monolingual adults successfully segmented two interleaved languages when they were presented by distinct voices, but that segmentation performance was diminished when the languages were presented by the same voice. The present experiments provided multiple cues to index the distinct languages. We cannot differentiate whether bilingual infants relied primarily on the pauses or voice or syllable information, or indeed whether they treated the two input streams as explicitly separate languages.

It is possible that bilinguals processed the dual speech streams as a single language with an 8-word vocabulary, produced in two distinct voices. As discussed above, experience with two languages may allow bilinguals to outperform monolinguals when there is a lot to learn, even when learning does not require tracking separate streams. Building on Weiss and colleagues' work with adults, we are investigating whether infants separate the speech streams by testing infants on two languages that share some of the same syllables. In this scenario, collapsing the statistical regularities into one large language produces conflicting transitional probabilities, which in turn could hinder segmentation.

In the present study, whether infants separated the languages or treated them as one large vocabulary, the indexing cues may have highlighted similarities across intervals of the same stream, thereby supporting learning (Erickson & Thiessen, 2015). Indexing information may be particularly salient to bilinguals, who must integrate across instances of a particular language in daily experience, despite these instances being separated by exposure to another language. This is consistent with the present findings, which indicate that the indexing cues were not sufficient to support monolingual infants' learning, but could support bilingual learning. It is possible that monolinguals would succeed in the task if the languages were more easily separable, with

the addition of cues to support language differentiation such as accent, prosody, or added speaker identification cues (i.e., video images of speakers).

Another consideration is that learning two sets of syllable regularities taxes memory and attentional control. Perhaps the young bilinguals in the present sample were able to employ inhibitory control or working memory more effectively than their monolingual counterparts due to prior experience navigating two languages. This view is supported by prior work suggesting bilingual advantages in executive functions during infancy and childhood (Barac & Bialystok, 2012; Carlson & Meltzoff, 2008; Kovács & Mehler, 2009a, 2009b; Nguyen & Astington, 2014; Poulin-Dubois et al., 2011). In related work with adults, Bartolotti, Marian, Schroeder, and Shook (2011) found that bilingual status was related to performance in a dual input statistical learning task. Monolingual and bilingual adults were exposed to two Morse code tone streams, and were then tested on recognition for sequences that formed 'words' in the Morse code input. Bilingual participants were more successful than monolinguals when interference was low across the two tone 'languages', which mirrors conditions in the present study. The authors suggested that bilinguals may have been more successful in that task due to a working memory advantage (e.g., Adesope et al., 2010; Nguyen & Astington, 2014).

If the cognitive consequences of bilingualism allow dual-language learners to process longer sequences of speech, maintain segmented words in memory for longer, or inhibit cross-linguistic interference to a greater extent than their monolingual peers, these benefits could facilitate statistical learning from dual input streams. Therefore, even if both groups track statistical patterns in a similar manner, bilingual experience may provide the additional support necessary for infants to learn the intricate patterns of interleaved languages. External support in the form of additional experience with the language stimuli, longer speech intervals, or more obvious cues to index the languages could allow monolinguals to segment the interleaved speech. To understand the underlying cognitive functions driving dual language segmentation, future research should probe the relationship between individual differences in memory capacity, inhibitory control, and dual language segmentation abilities in both infants and adults. Furthermore, if domain-general inhibitory control and working memory systems are influenced by bilingual exposure, bilingual infants should display a similar benefit in non-linguistic tasks that require tracking probabilistic patterns, such as dual sets of shape sequences (e.g., Kirkham, Slemmer, & Johnson, 2002) and sets of pure tones sequences (Saffran, Johnson, Aslin, & Newport, 1999).

7 | CONCLUSIONS

In conclusion, the present study provides the first evidence that infants can segment interleaved speech streams by tracking statistical regularities in the input and the first demonstration of statistical learning in bilingual infants. This impressive segmentation ability suggests that infants can track statistical regularities by integrating across multiple interactions in a particular language, even when these interactions are interspersed with speech in a different language. Furthermore, bilinguals' success in the segmentation task provides evidence that dual language learners are well equipped to exploit the statistical regularities present in their language environment. Despite experiencing language divided between two complex linguistic systems, bilinguals do not experience significant delays or impairments in language acquisition (Hoff et al., 2012). Previous research has suggested that bilingual experience may elicit positive consequences for attention and memory systems even in infancy (Brito & Barr, 2012, 2014; Kovács & Mehler, 2009a, 2009b; Singh et al., 2015), which in turn may support these remarkable learning abilities. Here, we propose that bilingual experience also lays a foundation for infants to track syllable regularities in interleaved speech streams, thereby promoting early access to two lexical systems and supporting bilingual acquisition.

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