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Review Article

Statistical Learning and Bilingualism

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Purpose: Over the last 2 decades, research on statistical learning has demonstrated its importance in supporting language development. Notably, most of the research to date has focused on monolingual populations (or has not reported the language background of participants). Several recent studies, however, have begun to focus on the impact of bilingualism on statistical learning. To date, the results have been quite mixed, with a handful of studies finding differences between monolinguals and bilinguals and several other studies reporting no differences. Thus, the purpose of this manuscript is to review the literature to date on how bilingualism impacts statistical learning abilities.
Method: We review the contemporary literature, organized by the age of participants and by task when relevant.
Conclusions: We note that there are many discrepant findings within this nascent field, although some trends have emerged. For instance, differences in performance may be attributed to factors such as age of acquisition. However, we note that the state of the field does not yet permit firm clinical recommendations.

Becoming proficient in two or more languages is ostensibly quite challenging. Learners must acquire multiple linguistic systems with sparser input in any given language relative to monolingual acquisition. For both receptive language input as well as language production, bilinguals obtain less experience with either language given that only one language can be produced at any given time (De Houwer, 2007; Gollan, Montoya, Cera, & Sandoval, 2008; Pearson, Fernandez, Lewedeg, & Oller, 1997; Scheele, Leseman, & Mayo, 2010). This sparser use of each language has been argued to result in some disadvantages for bilingual learners (a proposition known as the weaker links or frequency lag hypothesis; see Gollan et al., 2008, 2011). For example, bilinguals are slower at naming pictures relative to monolinguals, particularly when producing low-frequency labels (Gollan et al., 2008, 2011), and may be more susceptible to tip-of-the-tongue states (e.g., Gollan & Brown, 2006). In contrast to these drawbacks, the developmental literature is replete with evidence that young infants raised in a bilingual environment acquire language on a similar trajectory as their monolingual peers. They learn words and reach traditional language milestones at roughly the same pace as monolinguals (e.g., De Houwer, Bornstein, & De Coster, 2006; Werker & Byers-Heinlein, 2008). Moreover, the experience of learning and using two languages is thought to accrue cognitive benefits for bilinguals, evidenced from early infancy through older adulthood (Bialystok, 2011b; Byers-Heinlein, Morin-Lessard, & Lew-Williams, 2017; Goetz, 2003; Greenberg, Bellana, & Bialystok, 2013; Kovács & Mehler, 2009a; Perani et al., 2017; though see Paap, Johnson, & Sawi, 2015, for a dissenting view). For example, these advantages include faster inhibition of irrelevant information, improved performance shifting to a new task, and resolving conflicting information (Bialystok, 1999; Bialystok & Martin, 2004; Bialystok & Viswanathan, 2009; see also Kroll, Dussias, Bice, & Perrotti, 2014).

These contrasting views on bilingualism raise a particularly interesting question regarding the impact of bilingualism on the cognitive processes involved in the early stages of language learning. Over the last 20 years, much research has been devoted to understanding how domain-general learning may interface with language acquisition, particularly in the service of discovering language-specific cues to structure (e.g., Mattys, Jusczyk, Luce, & Morgan, 1999; Saffran & Thiessen, 2003). Specifically, a process known as "statistical learning" (SL) is thought to play a prominent role in early acquisition. SL is the process by which learners track distributional information in sensory input in order to detect the structure of the environment (see Weiss, 2014, for a brief overview).

SL in Language Acquisition

The initial study that brought SL to the forefront of the literature on language acquisition asked whether learners

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could use transitional probabilities between speech elements (e.g., syllables) to segment a continuous speech stream. Given that there are no consistent cues to speech segmentation that span every language (e.g., Klatt, 1976), the issue this initial study proposed to address was how infant language learners might initially come to identify discrete words embedded in speech. Consequently, Saffran, Aslin, and Newport (1996) tested whether 8-month-old infants could identify word boundaries in an artificial speech stream that could only be parsed by tracking rudimentary statistical cues (i.e., how often different sounds follow one another; termed transitional probabilities), controlling for other potential segmentation cues. Within words, transitional probabilities between syllables were high (i.e., one syllable was highly predictive of the next), but across word boundaries, the transitional probabilities dipped. Following familiarization to the artificial speech stream, infants heard isolated words or partwords (combinations of syllables that spanned word boundaries) from the stream, accompanied by a flashing light for visual fixation. Infants looked longer at the partwords, presumably due to their novelty, which suggests that they had successfully segmented the familiarization stream. In the adult version of the same task, the language was a bit more complex (i.e., additional words and more variable statistical cues), and learners were successful in identifying words versus partwords or nonwords (Saffran, Newport, & Aslin, 1996). These initial studies provided evidence that learners were sensitive to distributional regularities in speech and could use them to infer the structure of language input.

These findings prompted further studies to determine how SL might contribute to other aspects of language acquisition, such as phonetic learning (Maye, Weiss, & Aslin, 2008; Maye, Werker, & Gerken, 2002), word learning (Yu & Smith, 2007), and grammar learning (e.g., Gomez & Gerken, 1999; Reeder, Newport, & Aslin, 2013). Although many studies of SL have used artificial speech stimuli to maintain careful control over the acoustic properties of the input, SL has been shown to be effective for segmenting natural language input (Pelucchi, Hay, & Saffran, 2009). Moreover, SL abilities correlate with language proficiency measures later in life. For example, Newman, Ratner, Jusczyk, Jusczyk, and Dow (2006) found that infants who had demonstrated better speech segmentation performance during the first year of their lives had larger expressive vocabularies at 2 years of age (see also Evans, Saffran, & Robe-Torres, 2009). Speech segmentation abilities in the first year of life were also related to better syntactic and semantic language skills in the same group of children tested between 4 and 6 years of age (Newman et al., 2006). Even in the realm of literacy, SL has been found to correlate with reading ability for both elementary school children and adults (Arciuli & Simpson, 2012; see also Arciuli, 2018).

Multiple Components of SL

Given that learners track many types of statistical regularities, there has been an active discussion regarding whether SL is composed of a single process versus multiple components (see Arciuli, 2017; Batterink, Reber, Neville, & Paller, 2015; Marcovitch & Lewkowicz, 2009; Thiessen, Kronstein, & Hufnagle, 2012). The latter view suggests that different SL paradigms draw differentially on a similar suite of cognitive abilities (see Arciuli, 2017; Erickson & Thiessen, 2015; Hsu & Bishop, 2011). For example, learners may engage in two complimentary processes during SL: extraction and integration (Thiessen & Erickson, 2013). Extraction refers to the process by which statistically congruent clusters are held in working memory and bound together (e.g., Perruchet & Vinter, 1998). Integration is the process of combining information across stored clusters to identify the central tendency of the input (Erickson & Thiessen, 2015). Extraction is thought to rely on working memory and be guided by attention (Perruchet & Tillmann, 2010; Thiessen & Erickson, 2013), whereas integration may be more reliant on long-term memory processes (McClelland, McNaughton, & O'Reilly, 1995). All SL tasks are proposed to invoke these two processes to varying degrees (Erickson & Thiessen, 2015). The importance of understanding the demands imposed by different paradigms is that it may ultimately help explain the individual variability that is inherent to studies of SL (Arciuli, 2017; Siegelman, Bogaerts, & Frost, 2017; Siegelman & Frost, 2015). Moreover, with respect to the impact of bilingualism on SL, understanding the underlying cognitive demands of each task may ultimately shed light on why differences in performance between monolinguals and bilinguals are evident in some studies, but not others.

Incorporating Bilingual Perspectives to SL

Because the majority of the world is multilingual (Grosjean, 2010), it is natural to wonder whether SL is impacted by the experience of acquiring multiple languages. One of the central challenges of studying SL in multilingual populations is that, unlike monolingual acquisition, these groups are far more heterogeneous with respect to the course of language acquisition. Bilinguals may differ in a variety of ways, such as the age of acquisition (AOA) for each of their languages, the context in which the languages are learned and used, and overall proficiency within each language. Although simultaneous bilinguals learn two languages from birth, sequential bilinguals are monolingual until they become exposed to a second language at a later point in life. The age of first exposure to a second language for a sequential bilingual can vary greatly from as early as 3 years of age to older adulthood, and this typically has consequences for proficiency (e.g., Birdsong, 2005; J. S. Johnson & Newport, 1989). Furthermore, the age of the learner at test is also an important factor, given that one view of SL has been that the mechanism of SL is at its peak relevance during childhood (Reber, 1992; see also Arciuli, 2017). Although some studies have suggested that there are minimal differences in SL across ages (Kirkham, Slemmer, & Johnson, 2002; Saffran, Pollak, Seibel, & Shkolnik, 2007), others have found that SL abilities change across the life

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span (see Krogh, Vlach, & Johnson, 2013, for a review). The trajectory of SL abilities may differ by modality, as performance for visual SL has been found to improve over the course of development, whereas auditory SL abilities remain static (Raviv & Arnon, 2017). Thus, differences in SL in monolinguals and bilinguals could differ along this dimension as well.

The context in which each of a bilingual's two languages is acquired also impacts language outcomes. Bilinguals may live in a primarily bilingual environment or speak a heritage or minority language at home. Bilinguals' proficiency has been directly linked to the amount of exposure they receive in each of their languages (see Hammer et al., 2014, for a review) and the amount of time they spend speaking each language (Luk & Bialystok, 2013). Subsequently, bilinguals vary in their proficiency and dominance in each of their languages. Some bilinguals are considered more dominant in their first language, others are more proficient in their second language, and others are balanced and equally proficient in both of their languages.

The choice of experimental paradigm presents yet another consideration for measuring the impact of bilingualism on SL. As noted earlier, the majority of SL research to date has implicitly adopted a monolingual perspective, often testing monolingual learners (or groups with heterogeneous language backgrounds) with a single set of statistics to be acquired that remain uniform over the course of the experiment. Although this reductionist approach is useful for establishing the types of statistics that learners are capable of tracking (Aslin & Newport, 2014), it falls short of fully describing the problems that confront naive learners. Real-world environments are far less uniform, with variability stemming from different speakers, topic shifts, different dialects, and, of course, the possibility that there is more than one language being used (Qian, Jaeger, & Aslin, 2012; Weiss, Poepsel, & Gerfen, 2015). Consequently, learners must decide when the variability signals a shift to the underlying structure or represents variability within the existing structure. Thus, the challenge is knowing when to assimilate new statistics into an old representation versus accommodating by positing a new underlying model (much like Piaget, 1977). This facet of learning has consequences for bilingual learners, as evidenced, for example, by their relaxation of the mutual exclusivity constraint during word learning (Byers-Heinlein & Werker, 2009; Houston-Price, Caloghiris, & Raviglione, 2010).

In summary, given the vast amount of variability inherent in bilingual language acquisition, coupled with factors, such as the age of participants at test as well as the test type, it is not surprising that currently there is no consensus view on how bilingualism impacts SL. However, this has become a very active area of research. In this article, we review the current literature, organizing the findings by the age of participants, from infancy through adulthood, as well as by task (when relevant). We then consider whether there are translational applications for these findings and discuss future directions.

In searching for relevant articles to include, we were interested in articles that investigated the role of bilingual experience on linguistic or visual tasks requiring participants to track statistical regularities in the input. An additional goal was to review articles that simulated bilingual environments by presenting participants with multiple inputs (see Weiss et al., 2015). As an example of a search strategy employed to identify relevant articles, we used the keywords "statistical learning" and "bilingual*" in a search in PsycINFO, narrowing the search for "statistical learning" to "All subjects and indexing." After excluding dissertations, this search left 18 results. The minimum criteria for inclusion was that articles had to either use bilingualism as a factor (comparing monolinguals and bilinguals or using bilingualism as a continuous variable) or present learners with multiple sets of statistics. Furthermore, the article had to be an empirical study with the experimental task requiring tracking of probabilistic regularities. After excluding articles that did not meet these criteria, this resulted in eight articles that are discussed in the current review. Many of the additional studies reviewed here were drawn from citations, either articles that cited the aforementioned eight studies or articles that were referenced within that group of studies. To the best of our knowledge, the result of this effort effectively captures the current state of research on this topic.

SL and Bilingualism

Studies With Infants

One of the challenges confronting bilingual learners is forming multiple statistical representations to accommodate each language (e.g., Weiss, Gerfen, & Mitchel, 2009; Weiss et al., 2015). All infants, monolingual or multilingual, appear capable of discriminating languages from the same rhythmic class, provided that one of the two languages is their native language (Bosch & Sebastián-Gallés, 2001; Nazzi, Jusczyk, & Johnson, 2000). However, this perceptual ability likely does not necessitate forming separate representations for each language, as evidenced by the fact that tamarin monkeys (that have never been shown to form linguistic representations) are capable of making similar perceptual discriminations (Ramus, Hauser, Miller, Morris, & Mehler, 2000; Tincoff et al., 2005). SL studies may provide a more effective measure of multiple representations, as learners can be presented with multiple artificial languages and be asked to perform computations unique to each of the languages.

To date, however, few studies have directly tested whether bilingual infants exhibit any differences in SL relative to monolinguals. Antovich and Graf Estes (2017) tested 14-month-old monolingual and bilingual infants on an SL speech segmentation task (similar to the Saffran, Aslin, et al., 1996, study mentioned above) using two artificial languages with mutually exclusive syllable inventories, such that each syllable occurred in only one of the languages. After hearing alternating blocks of each language, they

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used a looking time procedure to determine whether words from each language could be distinguished from partwords (by longer looks to one class of tokens relative to the other). The infants raised in bilingual environments successfully segmented both streams, but the monolingual group did not. The authors suggest that the experience of learning multiple languages aided the bilingual group in tracking multiple sets of statistics. However, because the two languages used in this experiment did not overlap in their syllable inventory, the authors concede that it is possible that their stimuli could have been learned as a single structure. This latter interpretation opens the possibility that differences arose due to more general cognitive differences, such as differences in working memory capacity (e.g., Blom, Küntay, Messer, Verhagen, & Leseman, 2014; Garcia, Ros, Hart, & Graziano, 2018; Morales, Calvo, & Bialystok, 2013) rather than differences in the ability to form multiple representations or detect changes in SL.

Recent work in our lab has also been exploring this issue with 8-month-old infants using two partially overlapping artificial languages. This age range is particularly important, as it is similar to the original studies of SL (Saffran, Aslin, et al., 1996) and is a period in development in which infants may be using statistics to help infer language-specific cues for segmentation (E. K. Johnson & Jusczyk, 2001; Saffran & Thiessen, 2003). Unlike Antovich and Graf Estes, the two languages presented to infants had partial overlap in syllable inventory, such that a subset of the syllables were used in both languages. Therefore, infants could not combine information across streams and successfully learn both languages. Presentation of the two languages was blocked, and infants received 90 s of exposure to each language. Following familiarization, participants were tested on either the first language or the second language (rather than both) to minimize the difficulty of the task. Thus far, we have tested monolingual infants who were able to learn each language when presented in isolation. Separate groups of monolingual infants did not exhibit learning of either language when the two were presented in succession, even when one of the two languages was pitch shifted and a pause was introduced between the two languages (Bulgarelli, Benitez, Saffran, Byers-Heinlein, & Weiss, 2017). Ongoing work is exploring whether monolingual infants will be better able to form separate representations using more robust contextual cues, and our future work will test bilingual infants.

Our findings thus far suggest that forming multiple statistical representations is rather challenging using artificial languages, and this difficulty accords with research on natural speech segmentation. Although 6- to 8-month-old bilingual infants are capable of segmenting words from the language in which they receive more input (Bosch, Figueras, Teixidó, & Ramon-Casas, 2013), they may have more difficulty in segmenting the nondominant language. For example, Polka, Orena, Sundara, and Worrall (2016) tested whether English–French bilingual 8-month-old infants could segment speech in both of their languages. The infants were able to segment English speech streams but were only successful at segmenting bisyllabic words in a French speech stream (Polka et al., 2016). These findings further attest to the difference between discriminating two languages and forming multiple representations. Although the former appears to come readily to infants, the latter has a much lengthier developmental trajectory, which is mirrored in the aforementioned SL studies with multiple languages.

The difficulty in developing multiple representations may be mirrored in bilingual phonetic discrimination. Several studies have suggested that SL may play a central role in helping infants tune their phonetic discrimination to the native language by tracking distributional regularities of speech sounds (Maye et al., 2002, 2008). In natural language, for some speech sound contrasts, monolinguals and bilinguals appear to develop along similar trajectories (e.g., Burns, Yoshida, Hill, & Werker, 2007; Sundara, Polka, & Molnar, 2008), whereas for others, bilinguals experience protracted development (Bosch, 2010; Bosch & Sebastián-Gallés, 2003; Sebastián-Gallés & Bosch, 2009). Several factors likely contribute to these discrepancies. Most relevant to SL is the degree to which the distributions of sounds overlap across languages, as well as how much overall exposure learners receive (see Sebastián-Gallés, 2010; Sundara et al., 2008; Werker, 2012, for further discussion). Notably, like the SL studies described below, the process of discrimination may be facilitated by contextual cues (Sundara & Scutellaro, 2011). The larger picture is that more data are needed to address how different speech sound contrasts are discriminated in bilinguals relative to monolinguals. Interestingly, bilingual infants may employ strategies to help overcome the challenges presented by overlapping distributions. Specifically, bilingual infants attend to the mouth of a speaker earlier in development and over a longer period relative to monolingual infants. They do so when listening to both native and nonnative speech, indicating a greater reliance on redundant audiovisual information that may help to resolve fine-grained distinctions (Pons, Bosch, & Lewkowicz, 2015). In summary, the literature on forming multiple statistical representations in infancy points to a serious challenge for young learners.

Infants' ability to separate input generated from two potentially different sources has also been investigated in the realm of abstract rule learning. Initially, rule learning was posited to require a separate mechanism than SL (Marcus, Vijayan, Bandi Rao, & Vishton, 1999; Peña, Bonatti, Nespor, & Mehler, 2002), though subsequent accounts have suggested that abstract rules may be acquired through SL (see Aslin & Newport, 2012). Kovács and Mehler (2009a) tested monolingual and bilingual 7-month-old infants on their ability to learn multiple rules. Infants were first taught that a rule (e.g., items conforming to an A-A-B pattern such as wo wo fe or ga ga ti) led to a reward (the image of a toy) appearing on a specific location on the screen. Following nine trials of this rule, the rule changed (e.g., to A-B-A as in wo fe wo or ga ti ga) and the reward location changed to a different part of the display. They found that bilingual infants, but not monolinguals,

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were able to learn the new rule–location contingency, as gauged by the timing of their looking behavior to the new location after the switch had occurred (termed anticipatory looking, as the infants began looking prior to the appearance of the reward). In a similar experiment, Kovács and Mehler (2009b) tested 12-month-old monolingual and bilingual infants on their ability to learn two rules simultaneously. In contrast to the experiment with 7-month-old infants (Kovács & Mehler, 2009a), participants in this experiment were exposed to both types of rules (and their corresponding reward) during a single familiarization session. Following familiarization to both rules, infants were presented with novel stimuli that conformed to one of the two rules. Bilingual infants exhibited learning of both rules (as evidenced by anticipatory looking times), whereas monolingual infants only exhibited learning of both rules when there was a contextual cue differentiating the rules (i.e., each rule produced by a different speaker). Notably, however, this task could be solved by learning one rule and its inverse (i.e., the second location could correspond to anything other than the initial rule; see also Gonzales, Gerken, & Gómez, 2015, for how temporal context effects may impact learning). Together, these results suggest that there are differences in performance between monolinguals and bilinguals on rule learning tasks involving multiple rules. Like the SL experiments mentioned above, it is unclear whether these differences emanate from differences in rule learning (or SL) per se or arise as a consequence of bilingual advantages in other cognitive abilities (such as inhibitory control, which might allow learners to more readily overcome perseveration; Bialystok, 2011b; Byers-Heinlein et al., 2017; Goetz, 2003; Greenberg et al., 2013; Kovács & Mehler, 2009a; Perani et al., 2017).

To conclude, although the literature on bilingual SL in infancy is growing, at present there remain more questions than answers. There are indications that being raised in a bilingual home has consequences for SL, just as it has consequences for executive function (e.g., Barac & Bialystok, 2012; Kovács & Mehler, 2009a; Poulin-Dubois, Blaye, Coutya, & Bialystok, 2011). Thus, it is unclear whether differences in SL truly reflect different styles for accumulating or tracking statistics or whether they arise as a function of other cognitive differences. Although research with infants to date is not yet able to answer how early learners form separate representations for two languages, recent evidence shows that this is accomplished before 2 years of age (Byers-Heinlein et al., 2017).

Studies With Children

The experiments discussed above on bilingual infants are essentially studies of simultaneous bilinguals, as their exposure to a second language is concurrent with their acquisition of their first language. Far less is known regarding the SL abilities of early bilingual children, who may be simultaneous bilinguals or have acquired their second language after learning a native language. To our knowledge, there have only been three investigations of children who fall within this category. Yim and Rudoy (2013) investigated SL in 5- to 13-year-old Spanish–English bilinguals who were exposed to their second language starting at the age of 3. Their study compared these bilinguals to age-matched monolingual children on two SL tasks: a visual SL task in which subjects segmented triplet sequences from a stream of shapes and an analogous auditory SL task in which subjects segmented triplets from a stream of tones. In contrast to the differences reported for the simultaneous bilingual infants, monolingual and bilingual children performed similarly on both the auditory and visual tasks, leading the authors to conclude that bilingual experience does not impact SL.

Although bilingual children may not be advantaged in SL in the context of segmentation tasks, two studies have reported differences in other types of SL. Kuo and Anderson (2012) compared monolingual and bilingual kindergarteners to second graders (ranging from 6 to 9 years old) on their ability to learn phonological regularities in an artificial language. The children were exposed to an artificial language with a phonotactic pattern that was not present in either of their languages (Mandarin and Southern Min). During the test phase, learners were asked to choose between words that followed the phonotactic pattern and words that violated the pattern. Although all participants performed at above chance levels, the bilingual children significantly outperformed monolinguals, suggesting that exposure to a second language impacts learning new phonotactic regularities.

Bonifacci, Giombini, Bellocchi, and Contento (2011) compared bilingual children and adults on a series of tasks designed to evaluate the impact of bilingualism on nonverbal skills. This battery included a prediction task that is arguably related to SL. Participants were trained on a patterned sequence of colored rectangles. During anticipation trials, the stream would stop, and participants would be asked to report the color of the next rectangle. They tested two groups of participants: a group of 6- to 12-year-old children and a group of adolescents and adults spanning 14–22 years of age. Half of the participants in each group were bilinguals whose second language proficiency and AOA varied. The bilingual group showed overall faster response times on anticipation trials, and the authors suggest this may be due to an enhanced capacity for tracking statistical regularities in the input.

In summary, it is clear that there is a need for further research on bilingual children and SL. The dearth of data at this stage of development makes it difficult to draw firm conclusions regarding differences in SL relative to monolinguals. However, there is suggestive evidence that, for some types of SL, bilinguals seem advantaged relative to monolinguals, even those who have acquired their second language sequentially. As will be seen in the next section, acquiring a second language continues to impact SL even through adulthood.

Studies With Adults

Given the relative ease of testing adults in SL paradigms, it is not surprising that there are more studies with

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adult bilinguals relative to infants and children, as well as a wider variety of experimental paradigms. As adult bilinguals vary widely on language history and overall proficiency, there is a corresponding variance with respect to the outcomes of these studies. In this section, we break down the results by task and then discuss the larger implications from this body of work.

Speech Segmentation

In order to test whether language background impacts speech segmentation, Kittleson, Aguilar, Tokerud, Plante, and Asbjørnsen (2010) tested participants' ability to segment fluent Norwegian speech. Although all participants lived in Norway, none of them rated their proficiency in Norwegian above 2 on a scale of 1–10. Participants were divided into groups based on the origin of their primary language: Germanic, Indo-European excluding Germanic languages, or "other." Regardless of their language background, learners were able to segment the fluent Norwegian speech stream. The authors concluded that language background, including knowing multiple languages, did not significantly impact the SL abilities indexed by this task. Thus, like the Yim and Rudoy (2013) study with sequential bilingual children, this study further supports the notion that knowing multiple languages may not yield advantages in parsing a single speech stream.

Similar to the study by Kittleson and colleagues (2010), the majority of SL research has exposed learners to a uniform input whose statistics do not change over the course of familiarization. As real-world statistics contain far more variability, several studies have explored how learners may acquire two artificial languages. In order to simulate the challenge of bilingual speech segmentation, Weiss et al. (2009) exposed adult monolingual participants to two streams of speech, alternating exposure to each stream every 2 min for a total of 12 min per language. When the two streams were congruent, such that combining statistics across languages did not impact the probabilistic segmentation cues, learners successfully segmented both streams. However, when the two streams were incongruent, such that collapsing statistics across the languages interfered with the statistical structure in each language, learners acquired neither language unless the languages were differentiated by a contextual cue (in this study, a change in speaker voice, and in subsequent work, a visual cue to individual identity; see Mitchel & Weiss, 2010).

Using a similar experimental paradigm, Gebhart, Newport, and Aslin (2009) exposed participants to two incongruent speech streams with partial overlap in syllable inventory. Learners were exposed to 5 min of one artificial language, followed by 5 min of another. Under these conditions, participants exhibited a strong primacy effect, only successfully segmenting the first language. When one of the languages was pitch-shifted to resemble a change in speaker, learning of the second language trended toward significance. When an explicit cue was provided, along with a pause between languages, both languages were acquired (Gebhart et al., 2009). Using a variant of this procedure in which learners were intermittently tested on the learning of the first and second languages, Bulgarelli and Weiss (2016) found that both monolingual and bilingual participants exhibited similar performance. Although more research is needed, the results to date suggest that learning multiple inputs simultaneously poses a challenge for adult learners, regardless of language background, but contextual cues can help signal the shift in the underlying structure (see also Franco, Cleeremans, & Destrebecqz, 2011).

Although there may be similarities in how monolinguals and bilinguals acquire multiple statistical structures, a number of studies have found that sequential bilinguals are better able to contend with multiple cues in SL relative to monolinguals. Bartolotti, Marian, Schroeder, and Shook (2011) exposed participants to two artificial languages presented in Morse code with multiple possible cues to segmentation. In the low-interference condition, the transitional probabilities between the tones were congruent with pauses between statistically congruent segments. In the high-interference condition, the pause cues were incongruent with the transitional probabilities. Their participants were assigned to two groups: a low bilingual experience group, which reported an AOA of approximately 12 years of age, and a high bilingual experience group, which reported having acquired their second language at approximately 5 years of age. In the high-interference condition, both groups performed equally. In the low-interference condition, however, the high bilingual experience group outperformed the low bilingual experience group. The more experienced bilinguals may have been able to more effectively integrate across cues and use them together to identify segment boundaries. Alternatively, the bilinguals may have ignored one of the cues to segmentation and focused on the other. For example, in a monolingual SL study in which pause cues competed with statistical cues, performance on an inhibitory control task correlated with the ability to consistently follow only one of the two cues (Weiss, Gerfen, & Mitchel, 2010).

Consistent with the results reported by Bartolotti et al. (2011), Wang and Saffran (2014) also found that bilingual experience impacts SL when multiple cues are available for segmentation. The authors created an artificial speech stream that contained two congruent cues to segmentation: transitional probabilities and suprasegmental cues similar to those found in tonal languages. They tested monolingual English speakers, monolingual Chinese speakers (who have experience using tone contrastively in their native language), Chinese–English bilinguals, and an additional group of bilinguals who did not speak a tonal language. Participants in the two bilingual groups self-reported as being highly proficient in their non-English language. The Chinese–English bilingual group reported learning Chinese at home and English at school, whereas the nontonal language bilingual group reported speaking a language other than English at home or being fluent in another language. Monolingual English speakers did not perform above chance on the test of segmentation. However, both groups of bilinguals exhibited significant learning

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of the artificial language. Experience with a tonal language was not sufficient for learning, as the Chinese monolingual group did not exhibit above chance performance. As the suprasegmental cue proved to be a difficult cue for segmentation, the authors suggest that, as in the Bartolotti et al. (2011) study, the two groups of bilinguals were better able to ignore the suprasegmental cue to segmentation and focus only on the transitional probabilities between syllables to successfully segment the speech stream. Taken together, these two studies reveal an advantage for bilingual learners in the context of multiple cues to segmentation, possibly arising due to an ability to inhibit one cue and focus on the other.

Word Learning

As noted earlier, some types of SL tasks involve accruing information over time. One such paradigm is termed cross-situational SL (CSSL). The logic underpinning CSSL involves the indeterminacy of word learning, as learners in the process of matching words to their referents must contend with a near infinite number of possible definitions (e.g., Quine, 2013). Consequently, it has been argued that learners are constrained in their assumptions regarding how words map to objects, which serve to reduce the ambiguity (e.g., Markman & Wachtel, 1988). Similarly, the ability to accrue co-occurrence information across many scenes may also help resolve this problem (Yu & Smith, 2007). The CSSL paradigm, which has successfully been implemented with infants and adults (Smith & Yu, 2008; Yu & Smith, 2007), involves presenting learners with successive displays of novel objects (often ranging from two to four) and a corresponding number of nonwords that are presented in no particular order. Although each individual scene is ambiguous, by tracking co-occurrence information over successive scenes, learners can infer the correct mapping.

Several studies have investigated whether bilingual adults differ from monolinguals on this task. Escudero, Mulak, Fu, and Singh (2016) found that simultaneous Singaporean English–Chinese bilinguals were more accurate than monolingual English speakers on a CSSL task that involved learning phonologically similar words. By contrast, Poepsel and Weiss (2016) found that late learning Chinese–English and English–Spanish bilinguals performed equivalently to monolinguals in learning (phonologically distinct) word mappings. However, when some of the words were remapped in subsequent familiarization sessions, the bilinguals were faster and more accurate in their learning of the new mapping. The different results across CSSL studies may be due to differences in methodology (e.g., regarding phonological similarity) or the different language history of the bilinguals (late learning bilinguals in the Poepsel and Weiss study vs. simultaneous bilinguals in the Escudero study). Notably, the results of the study by Escudero and colleagues find some parallels in the explicit word learning literature in which bilinguals are advantaged relative to monolinguals (e.g., see Kaushanskaya & Marian, 2009). Likewise, bilingual infants are known to relax the mutual exclusivity constraint on word learning (the assumption that there is one label per object; see Byers-Heinlein & Werker, 2009; Houston-Price et al., 2010), a finding mirrored in the pattern reported by Poepsel and Weiss (2016).

Grammar Learning

The study of SL in bilinguals has recently been extended to grammar learning (Onnis, Chun, & Lou-Magnuson, 2017) using two artificial languages designed with simple grammars. The languages were audiovisual, with each individual artificial word paired with a novel shape. In order to provide a cue to the change in the artificial language, the shape and word inventories across languages were completely nonoverlapping. Across all participants, the rules of both artificial languages were learned with no difference between the two languages. Although this study did not directly compare performance to monolinguals, participants with a more balanced linguistic profile outperformed those who were more proficient in one of their two languages. To date, this is the only study that directly suggests an advantage for more balanced bilinguals in SL.

Summary of SL and Bilingualism

Although there are disparate findings across studies, some unifying themes are beginning to emerge from this body of research. First, becoming bilingual very early in life may lead to different outcomes relative to late learning bilinguals and monolinguals. In infancy, babies from a bilingual background appear advantaged in SL relative to monolinguals (Antovich & Graf Estes, 2017), and this may extend through adulthood, as well (Escudero et al., 2016). The impact of sequential bilingualism appears in more restricted contexts, such as when multiple competing cues are available in the input (Bartolotti et al., 2011; Wang & Saffran, 2014) and when participants have to learn multiple mappings or sets of rules (Onnis et al., 2017; Poepsel & Weiss, 2016). Furthermore, even for monolingual learners, when multiple structures are presented in the input, learning is possible if the switch between structures is correlated with a contextual cue related to speaker identity (Gebhart et al., 2009; Mitchel & Weiss, 2010; Weiss et al., 2009). It is conceivable that bilinguals hold an advantage early in development (e.g., Kovács & Mehler, 2009a, 2009b), though this has not been definitively established for SL (Antovich & Graf Estes, 2017; Bulgarelli et al., 2017). In the following section, we discuss the translational interface between SL and bilingualism with an eye toward practical applications for typical and atypical development.

SL and Language Outcomes

Although studies of SL and bilingualism point to a complex relationship, translating this laboratory research to real-world outcomes remains an important goal (e.g., see Weiss, Bulgarelli, Navarro-Torres, & Morales, 2017). As discussed in the introduction, learners' capacity for SL

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has been directly related to important markers of later language proficiency. For example, performance on a visual SL segmentation task was found to be correlated with performance on standardized reading tests for both children and adults (Arciuli & Simpson, 2012; see Arciuli, 2018, this issue, for a review). Performance on a visuomotor SL task correlated with receptive vocabulary measures, as well as performance on a sentence completion task, using both reaction time and event-related potential measures (Daltrozzo et al., 2017). Furthermore, in adult learners, artificial grammar learning has been found to correlate with online sentence comprehension (Misyak & Christiansen, 2012) as well as with more general measures of oral language proficiency, vocabulary knowledge, and phonological processing (Spencer, Kaschak, Jones, & Lonigan, 2015). SL abilities have been found to significantly correlate with the ability to predict upcoming words in a sentence perception task (Conway, Bauernschmidt, Huang, & Pisoni, 2010). In children, an SL segmentation task has been correlated with both receptive and expressive vocabulary (Evans et al., 2009). Correspondingly, deficits in SL have been linked to a variety of language-related disorders, such as specific language impairment (SLI; Evans et al., 2009) and dyslexia (e.g., Pavlidou, Louise Kelly, & Williams, 2010; though see Schmalz, Altoè, & Mulatti, 2017; see also Arciuli, 2018, this issue, for a brief review). Together, these findings suggest that the cognitive abilities inherent to SL interface in important ways with real-world language proficiency outcomes.

Given the relationship between SL and core features of language ability, it is not surprising that SL also bears predictive value for literacy acquisition in late second language learning. Frost, Siegelman, Narkiss, and Afek (2013) investigated this relationship in adult English speakers learning Hebrew, a language with very different statistical properties. They found that performance on a visual SL segmentation task correlated with better performance on acquiring the morphological regularities of Hebrew (measured using a morphological priming task), even after controlling for other cognitive abilities such as working memory (Frost et al., 2013). Although the sample size in this study was relatively small, the robust correlation between these abilities suggests that SL maintains relevance for real-world language learning outcomes into adulthood.

Sequence Learning as a Diagnostic Tool

As mentioned in the introduction, bilingualism can incur some costs for learners as a consequence of reduced exposure to either language during development (Gollan et al., 2008). Consequently, typically developing bilingual children may produce syntactic errors that arise as a consequence of constructions that are valid in their other language. These errors may resemble errors produced by monolingual children with SLI (e.g., Paradis, Crago, & Genesee, 2005; Park et al., 2018; Restrepo & Gutierrez-Clellen, 2001), leading to particular difficulty in diagnosing bilingual children with SLI. SLI is characterized by language difficulties in the absence of intellectual disabilities, neurological disorders, or other socioemotional dysfunctions (Leonard, 2014). Although there are standardized batteries of neuropsychological tests that are designed to identify language deficits in developing children, the normative data that are used as a comparison for individual performance is derived from monolingual children who are native speakers of English (Kohnert, 2010). Practitioners may be justifiably hesitant to administer these tests to bilingual children as the normative data are not representative.

With this in mind, a recent study compared monolinguals and bilinguals with SLI using a serial response time paradigm, essentially a visuomotor SL task in which continuous reaction time measures and accuracy of presses are used to gauge learning (Park et al., 2018). Participants are asked to press buttons that correspond to shapes appearing on the screen in different locations. Unbeknownst to the participants, the order of the shapes sometimes corresponds with an underlying pattern (e.g., Cherry & Stadler, 1995; Nissen & Bullemer, 1987; Willingham, Nissen, & Bullemer, 1989). As noted above, there is some evidence that bilingual children and adults produce faster reaction times relative to monolinguals on prediction tasks using similar methods (Bonifacci et al., 2011). Therefore, Park and colleagues (2018) investigated whether bilingual children with SLI may exhibit less difficulty with this type of implicit learning. The authors compared performance between typically developing monolingual and bilingual children and monolingual and bilingual children with SLI. Both groups of typically developing children exhibited learning of the patterned sequence, unlike either group of children with SLI. Thus, the results indicate that bilingualism does not spare children with SLI from SL deficits. However, direct comparisons between the SLI groups and the typically developing groups (for both monolinguals and bilinguals) did not yield significant differences. Thus, this study underscores the complexity of the relationship between bilingualism, language disorders, and SL outcomes. Future research will require much larger sample sizes in order to glean how bilingualism interfaces with SL (and all forms of implicit learning) for both school-age children and adults, as well as to determine whether these tests of learning can one day be incorporated into the diagnostic battery for bilingual children who may suffer from language impairments (e.g., see Kohnert, 2010).

Toward Developing Translational Outcomes for Clinicians and Researchers

As noted above, contemporary theories of SL suggest that it is composed of multiple complementary and interactive processes (e.g., Arciuli, 2017; Erickson & Thiessen, 2015). At first blush, adopting this view could benefit our understanding of how bilingualism impacts SL. For example, bilinguals are thought to be advantaged with respect to

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inhibitory control relative to monolinguals (e.g., Bialystok, Martin, & Viswanathan, 2005; Kroll, Bob, Misra, & Guo, 2008), and accordingly bilinguals outperform monolinguals on SL tasks that appear to involve an inhibitory component (e.g., Bartolotti et al., 2011; Wang & Saffran, 2014). Notwithstanding this correspondence, a principled understanding of when to expect differences between bilinguals and monolinguals remains elusive. True progress will require greater precision in identifying the cognitive and neural underpinnings of the different components of SL and how they may be indexed by different SL tasks (see Erickson & Thiessen, 2015, for further discussion). In turn, this precision will enable the development of diagnostic tools that may allow practitioners and educators to discriminate between bilingual learners at risk for language disorders from those who experience the typical effects of reduced exposure to a language (e.g., Gollan et al., 2008). Advancing toward this goal of developing diagnostic tools could benefit from a collaborative effort spanning researchers, clinicians, and educators (see Plante & Gómez, 2018, in this issue, for a proposal on how to integrate principles of SL into clinical assessments). Working together could help facilitate larger sample sizes for testing, thereby increasing the effectiveness and validity of any resulting intervention. Furthermore, this interdisciplinary approach will yield better translational outcomes, as it will be informed by developments and practices inherent in each discipline. By not restricting research to a laboratory setting, it is more likely that the resulting tools may be reliably administered in classrooms and clinical settings.

Concluding Remarks

Given the nascent state of the research investigating the effects of bilingualism on SL, it would be premature to draw any firm conclusions with respect to the current clinical implications of the impact of bilingualism on SL. Rather, as we note above, much more research is necessary to understand how all of the variables associated with bilingualism (such as proficiency, AOA, etc.) interface with the different measures used to gauge SL abilities, an endeavor that should be approached collaboratively. Nevertheless, it is worthwhile to point out that there is currently no direct evidence that bilingualism negatively impacts SL. To the contrary, there is evidence in infants (Antovich & Graf Estes, 2017) and adults (Bartolotti et al., 2011; Onnis et al., 2017; Poepsel & Weiss, 2016; Wang & Saffran, 2014) that bilingualism can lead to more successful learning outcomes under some circumstances. This accords with the now well-acknowledged notion in the scientific literature that the differences between monolingual and bilingual learners tend to be small (Bialystok, Luk, Peets, & Yang, 2010; Bosch & Sebastián-Gallés, 2003), with ample evidence that bilingualism may also result in some general cognitive benefits for children (Bialystok, 2011a; Carlson & Meltzoff, 2008), as well as clinical benefits much later in life, such as forestalling the onset of the symptoms of Alzheimer's disease (Bak & Alladi, 2014; Bialystok, Craik, & Freedman, 2007; Craik, Bialystok, & Freedman, 2010).

Understanding how bilingualism impacts SL, as well as other basic learning processes, may yield significant clinical advances. As noted above, one of the challenges posed by bilingual language acquisition is determining when bilingual learners have language deficits. Typically developing bilingual children may produce errors that resemble those produced by monolingual children who have deficits, perhaps as a consequence of constructions found in their second language (e.g., Paradis et al., 2005; Restrepo & Gutierrez-Clellen, 2001) or for other reasons, such as the reduced input in each language (Golan, et al., 2008; see Park et al., 2018). Consequently, an important step in identifying language impairment in bilinguals will be to develop assessment tools that can differentiate intrinsic deficits, such as developmental language disorder, from extrinsic factors, such as acquiring multiple languages, that produce similar errors in typically developing learners. In that context, future advances in understanding SL may provide some leverage for making this distinction, although, to date, this has not been successfully implemented (Park et al., 2018).

Another open question for future research concerns when learners are capable of forming separate representations for the two languages presented in their input. A relevant theme that has emerged from SL studies of multiple patterns is that forming these representations may be aided by contextual cues that correspond to a change in structure (e.g., Gebhart et al., 2009; Mitchel & Weiss, 2010; Weiss et al., 2009). Such studies find a parallel in the popular conventional wisdom of raising bilingual children, in which parents are instructed to speak only one language (termed one parent, one language [OPOL]). However, to date, there is little evidence to support this notion, as a large-scale questionnaire study by De Houwer (2007) suggested that OPOL was neither necessary nor sufficient for successful bilingual acquisition. Nevertheless, one direction for future research may be to explore more nuanced effects of providing rich cues to each language. For example, children raised in environments with more contextual cueing for their languages (e.g., OPOL) might be quicker to form multiple representations for each language (and consequently may develop earlier sensitivity to the languages spoken by their interlocutors; e.g., see Genesee, 2008).

In closing, one of the main challenges confronting research on SL and bilingualism is dealing with the types of variability inherent to research in each of these domains. Although the data thus far have been mixed, the problem is far from intractable. However, advances will require many more studies spanning bilinguals of different age ranges, levels of proficiency, and language pairings, as well as a variety of SL tasks. This provides a window of opportunity for clinicians, educators, and researchers to work together to develop tests that may not only further our understanding of the basic science consequences of bilingualism for SL but also yield diagnostic tools and perhaps interventions that can be deployed in classrooms and clinical settings.

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