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Second language learners develop non-native lexical processing biases

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Research Article

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Abstract

Infants develop language-specific biases favoring either consonantal or vocalic information. These phonological biases affect various levels of spoken-language recognition in children and adults. This study explored whether adults who speak a second language (L2) apply phonological biases during L2 lexical processing, and whether the biases applied are those of the native language (L1), or those appropriate for the L2. Two word reconstruction experiments were carried out in English and Mandarin Chinese. L1 and L2 speakers of English demonstrated a consonantal bias by changing English vowels faster than consonants. L1 and L2 speakers of Mandarin demonstrated a vocalic bias by changing Mandarin consonants faster than vowels. Even relatively late L2 classroom learners whose L1 triggers a consonantal bias (English) exhibited a vocalic bias in their L2 (Mandarin). Lexically related processing biases are thus determined by the phonological and lexical characteristics of the stimuli being processed and not solely by listeners' L1.

Introduction

It has been proposed that consonants and vowels play different functional roles during language processing (Nespor, Peña & Mehler, 2003). Nespor et al.'s division-of-labor hypothesis states that, irrespective of the language, vowels are more involved in prosodic and syntactic processes while consonants are more involved in lexically related processes such as speech perception (e.g., Bonatti, Peña, Nespor & Mehler, 2005; Delle Luche, Poltrock, Goslin, New, Floccia & Nazzi, 2014), written word recognition (e.g., New & Nazzi, 2014; New, Araùjo & Nazzi, 2008), and word learning (e.g., Nazzi, 2005; Havy, Serres & Nazzi, 2014; Havy, Bouchon & Nazzi, 2016; Havy & Nazzi, 2009; Nazzi & Bertoncini, 2009; Creel, Aslin & Tanenhaus, 2006). This observed consonant-vowel asymmetry has even led to the proposal that all listeners exhibit an initial bias for consonantal information during lexically related processing (Bonatti, Peña, Nespor & Mehler, 2007; Nespor et al., 2003).

Findings from developmental research, however, suggest that such biases are language-specific; processing biases develop as a by-product of the acoustic-phonetic and lexical properties of the language (Højen & Nazzi, 2016; Floccia, Nazzi, Delle Luche, Poltrock & Goslin, 2014). While research has begun to understand how processing biases emerge in children acquiring their first language (L1; e.g., Sebastián-Gallès, Echeverria & Bosch, 2005; Bosch & Sebastián-Gallès, 2003; Mani & Plunkett, 2010; Nazzi, Floccia, Moquet & Butler, 2009; Poltrock & Nazzi, 2015; Nazzi & New, 2007; Nishibayashi & Nazzi, 2016; Singh, Goh & Wewalaarachchi, 2015), it remains unclear whether similar biases develop in adults acquiring a second language (L2). Moreover, if phonological biases emerge in an L2, it is an open question whether they are determined through a transfer from native to non-native processing or in response to the properties of the L2 input. The present study addresses these questions by examining L1 and L2 listeners' lexically related consonantal and vocalic biases in English and Mandarin Chinese.

Origins of L1 processing biases

Research into L1 acquisition has identified at least two potential factors involved in the developmental origin of consonantal and vocalic processing biases (see Nazzi, Poltrock & Von Holzen, 2016; Nazzi & Cutler, 2019 for reviews). The "acoustic-phonetic hypothesis" (Floccia et al., 2014) posits that a bias emerges as a result of the various acoustic and phonological phenomena present in a learner's input. Languages vary with respect to the proportion of consonants and vowels in the phonological inventory, how these cues are realized in speech, and each cue's relative informativeness across prosodic, syntactic, and lexical levels. These language-specific differences may modulate the functional role of consonants and vowels (Højen & Nazzi, 2016; Nazzi et al., 2016; Floccia et al., 2014). For instance, spoken Danish exhibits a relatively high degree of consonant lenition (Pharao, 2011; Grønnum, 1998; Basbøll, 2005), which increases the informativeness of Danish vowels. Mandarin Chinese

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(hereafter 'Mandarin') serves as another example. Mandarin vowels carry lexically contrastive fundamental frequency (F0) information (Ho, 1976; Xu, 1999; Gandour, 1983). This tonal information constrains lexical access immediately, plays a role comparable to that of segments, and makes vowels more informative than consonants (e.g., Malins & Joanisse, 2010, 2012; Zhao, Guo, Zhou & Shu, 2011; Wiener & Ito, 2015; Wiener & Turnbull, 2016; Tong, Francis & Gandour, 2008; Repp & Lin, 1990; Lee & Nusbaum, 1993; Gómez, Mok, Ordin, Mehler & Nespor, 2018). Prioritizing vocalic information may be advantageous for Danish learners, if not essential for Mandarin learners. Speakers of these languages may therefore develop a bias for vocalic information (V-bias) during infancy (e.g., Højen & Nazzi, 2016; Singh et al., 2015; Wewalaarachchi, Wong & Singh, 2017).

The second potential factor contributing to the development of phonological biases reflects linguistic experience at the lexical level. This "lexical hypothesis" (Keidel, Jenison, Kluender & Seidenberg, 2007) states that consonant-vowel asymmetries exist in each language, which cause one broad category of cues to be more informative for coding differences in a speaker's lexicon. For many European languages, consonants outnumber vowels and are therefore more informative for lexical distinctions, i.e., more neighbors can be attained by changing a consonant than a vowel (Hochmann, Benavides-Varela, Nespor & Mehler, 2011). As a result, speakers of English, Spanish, and Dutch (among other languages) develop a bias for consonantal information (C-bias) during infancy (see Nazzi and Poltrock, 2016). In other languages, vowels may be more informative for lexical distinctions. According to the lexical hypothesis, Danish-learning infants may develop a V-bias because Danish vowels outnumber Danish consonants, i.e., the Danish lexicon contains more neighbors that can be attained by changing a vowel than a consonant (Højen & Nazzi, 2016; Bonatti et al., 2007).

Thus, a C- or V-bias emerges during infancy as a by-product of the phonological and/or lexical properties of the input. Yet, it remains largely unknown how a fully developed L1 phonological bias affects adults' lexical processing of non-native speech. Limited evidence from adult artificial language learning suggests that, once a C- or V-bias is acquired in infancy, it may become independent of lower-level acoustic-phonetic differences in speech (e.g., Toro, Nespor, Mehler & Bonatti, 2008a; Toro, Shukla, Nespor & Endress, 2008b). For example, Toro et al. (2008b) created an artificial language in which rules and words were implemented over vowels or consonants. Adult speakers of a language that elicits a C-bias (Italian) used vowels for structural generalizations and consonants for statistical computations. This pattern remained even after the acoustic features of consonants were made more salient and vowels less audible. Toro et al.'s findings imply that while lower-level acoustic differences may affect the acquisition of an L1 phonological bias during early development, these acoustic differences appear to no longer play a direct role in adult processing of (non-native) speech.

While the artificial language learning approach (e.g., Toro et al., 2008a, 2008b; Creel et al., 2006) has advanced our understanding of processing biases and refined the acoustic-phonetic hypothesis, this approach has two limitations. First, input is typically restricted to short lab-based training sessions. Although developmental research has revealed that biases emerge rapidly in infants – French and Italian infants demonstrate a C-bias from 8 months onward (e.g., Nazzi, 2005; Hochmann et al., 2011; Poltrock & Nazzi, 2015; Nishibayashi & Nazzi, 2016) – limited lab-based input may be insufficient for phonological biases to fully develop in a native-like manner. Second, artificial language learning studies like Toro et al. (2008a, 2008b) cannot speak to whether lexical properties affect adult listeners' development and application of phonological biases. In this context, behavioral results from adults learning an artificial language may be confounded by the lack of a lexicon.

To overcome these two limitations, the present study examines processing biases in adult L2 learners. This approach allow for a more ecologically valid test of how extended non-native input and L2 lexical development affect adults' phonological biases in lexical processing.

Word reconstruction task

To examine how previously acquired phonological biases may be applied given new input, this study uses the word reconstruction task (van Ooijen, 1996). In this task, a participant hears a spoken nonword and is asked to orally report a word that can be created through a single consonant or vowel substitution; response time and accuracy serve as dependent measures. For example, the English nonword /ɛltəmət/ can become "ultimate" through a vowel change or "estimate" through a consonant change. This task ensures that lexical access takes place, allows for a direct comparison of the effect of consonant and vowel using the same experimental item between subjects, and removes any potential orthographic confounds. Crucially, the nonword stimulus functions as the "PERCEPTUAL TEMPLATE of multiple real words" (van Ooijen, 1996). These perceptual templates force listeners to activate concurrent lexical candidates containing similar sounding speech cues, constrain all competitors, and ultimately select an intended word, thus mimicking the processes involved in spoken word recognition (e.g., McQueen, Norris & Cutler, 1994, 1999; Marslen-Wilson, 1990; Samuel, 2011; Cutler, 2012; Connine, Blasko & Wang, 1994; Shillcock, 1990; Vitevitch & Luce, 1998, 1999).

In van Ooijen's seminal study (1996), native English listeners changed vowels faster and more accurately than they changed consonants. In a third condition, listeners were free to change either the vowel or the consonant. Given this free choice, participants changed vowels more often and faster than they changed consonants. Replications were run with Spanish and Dutch stimuli, thus providing a further manipulation of vocabulary structure as a possible determinate of the biases (Cutler, Sebastián-Gallès, Soler-Vilageliu & van Ooijen, 2000; see also Sharp, Scott, Cutler & Wise, 2005; Marks, Moates, Bond & Stockmal, 2002; Cutler & Otake, 2002). Irrespective of the language tested, participants in these word reconstruction studies exhibited a lexically related C-bias.

These original reconstruction studies, however, exclusively tested listeners of European languages that share relatively similar phonological and lexical characteristics. As a result, the observed C-bias in van Ooijen (1996) and Cutler et al. (2000) may have reflected the phonological and/or lexical properties of English, Spanish, and Dutch. Wiener and Turnbull (2016) expanded the reconstruction paradigm by testing listeners of Mandarin – a language with heavily constrained syllable phonology in which syllables are maximally (C)V(C), carry a lexical tone, and can stand alone as a morpheme or word (DeFrancis, 1986; Packard, 2000; Duanmu, 2007, 2009; Zhou & Marslen-Wilson, 1994, 1995). Wiener and Turnbull also added a tone change condition in which listeners had to change one of four lexically contrastive F0 contours. For example, participants heard the Mandarin

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nonword /su/ with the low-dipping tone (Tone 3). Depending on the condition the stimulus was presented in, participants could change the tone to create *su4* ("fast"), the vowel to create *si3* ("death"), or the consonant to create *tu3* ("soil"). Unlike listeners tested in the previous European language reconstruction studies, Mandarin listeners demonstrated a lexically related V-bias: participants changed consonants faster and more accurately than they changed vowels. In the free choice condition, consonant changes outnumbered vowel changes. Wiener and Turnbull concluded that the observed V-bias was a by-product of Mandarin's phonological and lexical properties.

Yet, Wiener and Turnbull's results should be interpreted with caution. First, unlike the Cutler et al. (2000) and van Ooijen (1996) stimuli, which counterbalanced the position of the consonant and vowel change across multisyllabic nonwords, Wiener and Turnbull's stimuli consisted exclusively of monosyllabic nonwords with initial consonant changes. Stimuli of this nature were unavoidable since the Mandarin lexicon contains predominantly consonant initial words. Calculations based on the 33.5 million word corpus SUBTLEX-CH (Cai & Brysbaert, 2010) suggest that only around 15% of the Mandarin lexicon contains vowel initial words, such as *ang1* ('filthy'). Thus, Wiener and Turnbull's reconstruction results may have been partially confounded by the positional effects of the consonant and vowel changes.

Additionally, because Wiener and Turnbull tested participants using Mandarin instructions, the task involved changing the initial and final, i.e., language-specific terms more familiar to Mandarin speakers than the western terms for consonant and vowel. As a result, the authors did not test whether stimuli containing a nasal coda or changes to the final involving the addition of a nasal coda differed in response time or accuracy. Because changing a Mandarin final may fundamentally differ from changing a vowel, one aim of the present study is to clarify Wiener and Turnbull's previous findings.

In summary, the word reconstruction task captures listeners' language-specific phonological biases in lexical processing. Previous reconstruction results indicate that English-L1 speakers exhibit a C-bias while Mandarin-L1 speakers exhibit a V-bias. To examine whether non-native speakers exhibit a C- or V-bias in their L2 and, if so, to what degree such biases are transferred from their L1 or reflect the phonological and lexical information of the stimuli being processed, a series of word reconstruction experiments were carried out. In Experiment 1, English-L1, Spanish-L1, and Mandarin-L1 speakers were tested on English stimuli. The goal of Experiment 1 was to determine whether participants demonstrate the same C-bias in their word reconstruction responses irrespective of their L1. The use of the two L2 groups allowed for a cross-linguistic comparison between speakers who demonstrate an L1 C-bias (Spanish; Cutler et al., 2000) and those who demonstrate an L1 V-bias (Mandarin; Wiener & Turnbull, 2016).

Experiment 1A: reconstruction in English as an L1

Method

Participants

Twenty-seven native English speakers (13 male; 14 female; mean age = 21.3; *SD* = 3.1) from the United States participated in Experiment 1A. All participants were students at an American university, had normal hearing and speech, and had previously studied a European L2 (Spanish, Latin, Italian, French, or German) for three years or less in secondary school. No participant continued to study or speak an L2. All participants in this and the other experiments reported here were paid or given class credit for their participation.

Materials

Sixty nonwords taken from van Ooijen's (1996) study were used as stimuli (see Online Supplementary Materials for full stimuli and all possible changes). Each nonword could be turned into a real English word by changing either a consonant or a vowel. Position of change was roughly controlled for: 35 of the 60 words involved a consonant change before a vowel change while the remaining 25 words involved a vowel change before a consonant change. Roughly half of the nonwords involved more than one possible consonant or vowel change. An additional 70 nonwords were created as fillers along with 12 practice items. The stimuli were recorded at 44.1 kHz with 16-bit resolution using a sound attenuated booth. To ensure that each nonword was acoustically as close as possible to both its alternatives, a phonetically trained female native English speaker first pronounced both the vowel and the consonant real-word alternative before each stimulus nonword i.e., "ultimate, estimate, *eltimate*". The order of vowel and consonant recordings was counterbalanced across recordings.

The 60 nonwords were randomly divided into three groups of 20. These groups were rotated across three change conditions, resulting in a within-subject design. Thus, all participants heard the 60 nonwords: a third heard *eltimate* in the vowel condition, a third heard *eltimate* in the consonant condition, and a third heard *eltimate* in the free choice condition.

Procedure

Participants were tested individually in a quiet lab using headphones. Participants first answered a brief language background questionnaire, after which they were given printed and oral instructions that they would hear English nonwords. Depending on which condition the listeners were in (e.g., consonant, vowel or free), participants were told to change a particular sound such that a real-word could be produced. Participants were given four practice trials (with example answers) for each condition and explicitly told to think about the word's sound and not its spelling. As soon as participants thought of a word, they were asked to say the word aloud into a microphone. Participants were not made aware beforehand that they would be asked to make other phonemic changes in other conditions; condition presentation order was counterbalanced across participants. Stimuli were presented using E-prime (Psychology Software Tools, Inc., 2012) with a 10 second timeout period if no response was given. After each trial, participants were required to press a button to proceed to the next trial with a two-second ISI. Verbal responses and response times measured at word onset were recorded using the Chronos response and stimulus device and voice key (Babjack, Cernicky, Sobotka, Basler, Struthers, Kisic, Barone & Zuccolotto, 2015). This method of response time logging differed from van Ooijen's (1996) original methodology, which required participants to first press a key before speaking. The experiment took approximately 30 minutes.

Results and discussion

Oral responses were transcribed by a native English speaker. Roughly 5% of responses were removed due to timeout errors (no response given within 10 seconds) or false alarm responses

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(participants began to respond but stopped before producing a word). The remaining responses were scored as correct or incorrect changes. Because some trials allowed for multiple answers (e.g., "task" or "tusk" for /tɪsk/ in the vowel change condition), any response that involved the appropriate change was scored as correct. Changes that did not follow the instructions, such as a consonant change in the vowel change condition (or vice versa), or changes involving multiple speech sounds were scored as incorrect. Table 1 presents mean error rates and mean correct response times (RT) for the three conditions.

To test whether error rates and correct response times were statistically different across conditions, mixed-effects logistic regression (accuracy) and linear regression (log transformed RT of correct responses) models were built using the *lme4* package (Bates, Maechler, Bolker & Walker, 2015) in R version 3.3.3 (R Core Team, 2017). This statistical approach was used, as it allows for simultaneous consideration of all the factors that potentially contribute to the data, and tests that observed effects are robust over items and participants (Baayen, Davidson & Bates, 2008; Barr, Levy, Scheepers & Tily, 2013). Each model's effects structure was evaluated using the *lmerTest* package (Kuznetsova, Brockhoff & Christensen, 2017) in R, which allows for the elimination of non-significant fixed and random effects.

The logistic regression model included two fixed effects. Participants' condition (vowel, consonant, free) was contrast coded with the consonant choice as the reference level allowing for two planned contrasts: consonant-vowel and consonant-free. Position of change, i.e., whether a consonant or vowel change came first, was included as a sum coded effect. Random by-participant and by-item intercepts and random slopes for condition were included. R formula: accuracy ~ condition + position +(1|subject) + (condition|item). The linear regression model included the same variables and effects structure but tested correct response times. R formula: log RT ~ condition + position +(1|subject) + (condition|item). Reported p-values for *t*-distributions were obtained using the *lsmeans* package (Lenth, 2016).

Vowel accuracy was marginally higher than consonant accuracy ($\beta = 0.78$, $SE = 0.46$, $z = 1.67$, $p = .09$); free choice accuracy was significantly higher than consonant accuracy ($\beta = 1.60$, $SE = 0.47$, $z = 3.34$, $p < .001$). Position of consonant/vowel change did not affect overall accuracy ($\beta = 0.02$, $SE = 0.45$, $z = 0.06$, $p = .95$).

Vowel response times were significantly shorter than consonant response times ($\beta = -0.21$, $SE = 0.09$, $t = -2.23$, $p = .04$); free choice and consonant response times did not differ ($\beta = -0.09$, $SE = 0.09$, $t = -0.98$, $p = .51$). Position of consonant/vowel change did not affect response times ($\beta = 0.04$, $SE = 0.08$, $t = 0.53$, $p = .60$).

Subset analyses of the free choice responses indicated that participants changed vowels significantly faster (2,546 ms) than they changed consonants (2,905 ms) ($\beta = 0.19$, $SE = 0.08$, $t = -3.39$, $p < .001$) and made marginally more vowel changes (56%) than consonant changes (44%) ($\chi^2(1) = 2.92$, $p = .08$).

The response time results in Experiment 1A corroborate van Ooijen's (1996) finding: English-L1 speakers exhibit a C-bias by changing vowels faster than consonants. With respect to accuracy, participants were marginally more accurate at changing the vowel and marginally preferred vowel changes to consonant changes when given the free choice. This marginal effect of condition on response accuracy was unexpected given van Ooijen's fairly robust accuracy difference. This difference between the two studies may be attributed to the present study's different response methodology, the use of U.S. English speakers as opposed to British English speakers, the lower error rate of the participants tested in Experiment 1A (31% error rate in the consonant condition as compared 42% in van Ooijen), or the more conservative mixed-effects statistical modeling approach (see Quené & Van den Bergh, 2008; Barr et al., 2013; Matuschek, Kliegl, Vasishth, Baayen & Bates, 2017).

Despite the marginal effect of condition on response accuracy, Experiment 1A's response time results serve as evidence that English-L1 speakers exhibit a C-bias during lexical processing. Moreover, the null effects of consonant/vowel position on accuracy and response times confirm that these results were not driven by the position of the consonant and vowel change in the nonword stimuli. Experiment 1B next clarifies whether Spanish-L1 English-L2 speakers exhibit a similar C-bias while processing English-L2 speech.

Experiment 1B: reconstruction in English as an L2 (Spanish-L1)

Method

Participants

Twenty-seven native Spanish speakers from nine countries in Latin and South America participated in Experiment 1B. All participants spoke English as an L2, had normal hearing and speech, had completed up to high school in their home country, and were currently studying at an American university. See Table 2 for additional participant information including self-assessed and objective L2 proficiency levels.

Materials and procedure

The materials and procedure were identical to those of Experiment 1A with the instructions given in Spanish and English. Though van Ooijen's (1996) original stimuli were designed to ensure that all potential consonant-change and vowel-change words were high frequency words, four additional non-native English speakers from the same population as the participants (none of whom participated in the study) were asked to orally define the 120 target words. All participants defined the words with 100% accuracy.

Results and discussion

Oral responses were transcribed by a native English speaker and two non-native English speakers from Argentina and China, respectively. Roughly 7% of responses were removed due to time-out errors, false alarm responses or a lack of transcriber agreement. Table 1 presents mean error rates and mean correct response times by condition. To test whether Spanish-L1 participants' error rates and correct response times were statistically different across conditions, mixed effect models were built identical to those outlined in Experiment 1A.

Vowel accuracy was significantly higher than consonant accuracy ($\beta = 1.24$, $SE = 0.49$, $z = 2.51$, $p = .01$); free choice accuracy was significantly higher than consonant accuracy ($\beta = 1.45$, $SE = 0.45$, $z = 3.17$, $p < .01$). Position of consonant/vowel change did not affect overall accuracy ($\beta = 0.65$, $SE = 0.56$, $z = 1.16$, $p = .24$).

Vowel response times were significantly shorter than consonant response times ($\beta = -0.18$, $SE = 0.09$, $t = -2.01$, $p = .04$); response times did not differ between the free and consonant conditions ($\beta = 0.06$, $SE = 0.07$, $t = 0.81$, $p = .69$). Position of consonant/vowel change did not affect response times ($\beta = 0.08$, $SE = 0.05$, $t = 1.46$, $p = .15$).

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Table 1. Mean error rates (%) and correct response times (ms) in Experiments 1 & 2.

		Error Rates (%)				Response Times (ms)			
Experiment 1: English Reconstruction									
		Condition							
		V	C	F		V	C	F	
Experiment	**Group**								
1A	English-L1	21	31	11		2,311	2,915	2,710	
1B	Spanish-L1	29	50	23		2,353	3,010	3,032	
1C	Mandarin-L1	24	51	27		3,033	3,652	3,234	
Experiment 2: Mandarin Reconstruction									
		Condition							
		V	C	F	T	V	C	F	T
Experiment	**Group**								
2A	Mandarin-L1	51	32	14	15	4,117	3,429	2,323	2,071
2B	Mandarin-L2	60	50	25	13	4,204	3,568	3,120	2,371

Condition abbreviations: V = Vowel, C = Consonant, F = Free, T = Tone

Given the free choice, participants changed vowels significantly faster (2,755 ms) than consonants (3,295 ms) ($\beta = 0.13$, $SE = 0.06$, $t = 2.01$, $p = .04$) and made marginally more vowel changes (58%) than consonant changes (42%) ($\chi^2(1) = 3.36$, $p = .07$).

The results from Experiment 1B establish that Spanish-L1 English-L2 speakers exhibit an English C-bias; vowels were changed faster and more accurately than consonants. These results were independent of the position of the consonant/vowel change, mirror the asymmetric pattern observed in Spanish-L1 speakers performing the task in their native language (Cutler et al., 2000), and replicate the English-L1 speakers' results from Experiment 1A. More importantly, Experiment 1B's results serve as initial evidence that non-native speakers exhibit a lexically related phonological bias during L2 lexical processing.

Because Spanish-L1 speakers demonstrate a C-bias in their native language (Cutler et al., 2000), the results from Experiment 1B may have been, in part, due to a transfer from the L1 processing system. The goal of Experiment 1C was to examine the behavioral patterns of speakers whose L1 (Mandarin) elicits a V-bias in their lexical processing. If L2 processing biases are transferred, Mandarin-L1 English-L2 speakers should change consonants faster and more accurately than they change vowels. If listeners apply a new processing bias in accordance with their L2, participants should change vowels faster and more accurately than they change consonants.

Experiment 1C: reconstruction in English as an L2 (Mandarin-L1)

Methods

Participants

Twenty-seven native Mandarin speakers from Mainland China participated in Experiment 1C. All participants spoke English as an L2, had normal hearing and speech, had completed up to high school in China, and were currently studying at an American university. See Table 2 for additional participant information.

Materials and procedure

The materials and procedure were identical to those of Experiment 1A and 1B with the instructions given in Mandarin and English. The words for 'consonant' and 'vowel' were used in both the English and Mandarin instructions.

Results and discussion

Oral responses were transcribed by a native English speaker and two non-native English speakers from China. Roughly 6% of responses were removed due to timeout errors, false alarm responses or a lack of transcriber agreement. Table 1 presents mean error rates and mean correct response times for the three conditions. To test whether Mandarin-L1 participants' error rates and correct response times were statistically different across conditions, mixed effect models were built identical to those outlined in Experiment 1A.

Vowel accuracy was significantly higher than consonant accuracy ($\beta = 1.58$, $SE = 0.49$, $z = 3.19$, $p < .01$); free choice accuracy was significantly higher than consonant accuracy ($\beta = 1.27$, $SE = 0.48$, $z = 2.62$, $p = .01$). Position of consonant/vowel change did not affect overall accuracy ($\beta = 0.43$, $SE = 0.48$, $z = 0.88$, $p = .37$).

Vowel response times were significantly shorter than consonant response times ($\beta = -0.19$, $SE = 0.08$, $t = -2.29$, $p = .04$); response times did not differ between the free and consonant conditions ($\beta = -0.14$, $SE = 0.08$, $t = -1.64$, $p = .24$). Position of consonant/vowel change did not affect response times ($\beta = 0.01$, $SE = 0.06$, $t = 0.05$, $p = .96$).

Given the free choice, participants changed vowels (3,068 ms) and consonants (3,493 ms) with similar response times ($\beta = -0.03$, $SE = 0.07$, $t = 0.34$, $p = .73$). Participants made significantly more

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Table 2. Demographics and self-assessed proficiency measures of non-native participants tested in Experiments 1B, 1C, and 2B (results represent group means and standard deviations).

	Experiment 1B	Experiment 1C	Experiment 2B
Age	30.4 (5.3)	24.6 (3.2)	21.7 (3.7)
Gender	14M; 13F	12M; 15F	12M; 12F
L1	Spanish	Mandarin	English
L2	English	English	Mandarin
Current L2 immersion	Yes	Yes	No
Estimated daily percentage of exposure to language			
L1	14 (8)	16 (14)	87 (6)
L2	84 (10)	81 (12)	11 (15)
Self-rated L2*			
Speaking	3.8 (.4)	3.6 (.5)	3.1 (.5)
Listening	3.8 (.4)	3.7 (.4)	3.2 (.5)
Age of L2 acquisition	8.5 (.9)	7.5 (1.0)	18.7 (3.4)
Length of residence in L2-			
speaking country (years)	4.3 (1.3)	2.2 (2.1)	0.0 (0)

*1: beginner; 2: intermediate; 3: advanced; 4: native-like

vowel changes (58%) than consonant changes (42%) ($\chi^2(1) = 6.22, p = .01$).

The results from Experiment 1C establish that Mandarin-L1 English-L2 speakers exhibit a C-bias during English lexical processing: English vowels were changed faster and more accurately than consonants. These results were independent of the position of the consonant/vowel change. When given the free choice, participants preferred vowel changes to consonant changes, though the two categories were changed with similar response times.

Summary of Experiment 1 – English reconstruction

Figure 1 plots individual data points per item (correct RT) and per participant (error rate), violin plots for each condition, 95% confidence intervals (black box), and condition means (white line within confidence interval box). Figure 1 illustrates that participants in all three groups demonstrated a similar C-bias during word reconstruction by changing vowels faster than consonants and changing vowels, on average, more accurately than consonants.

The results from Experiment 1 indicate that adult L2 acquisition involves the development and application of a phonological bias during L2 lexical processing. The phonological bias applied may be similar to a listener's L1 bias: a C-bias was found in non-native English processing by adults that are native speakers of a C-bias eliciting language (Spanish). Additionally, the bias applied may be different from a listener's L1 bias: a C-bias was found in non-native English processing by adults that are native speakers of a V-bias eliciting language (Mandarin).

Adults familiar with the phonological and lexical traits of two languages appear to adapt their phonological bias to the specific demands of the language. Experiment 1C's results suggests that (potential) L1 transfer of biases can be avoided if the L2 demands it. It should be noted, however, that these findings do not necessarily exclude the possibility that the C-bias observed in Spanish-L1 speakers in Experiment 1B was solely due to L1 transfer. Different mechanisms may apply to these two very different bilingual situations.

Taken together, Experiment 1's results support the claim that processing biases develop in response to the phonological and lexical properties of the input. Experiment 2 extends Experiment 1 by using Mandarin as the target language and testing Mandarin-L1 and Mandarin-L2 speakers. Experiment 2 also serves as an initial investigation into whether constraints on the amount of L2 input and a listener's age of acquisition affect the development and application of a new processing bias. Thus, the non-native participants tested in Experiment 2 differed from the non-native participants tested in Experiment 1 in two critical ways.

First, the participants tested in Experiment 2B had a mean age of acquisition nearly a decade later than that of the participants tested in 1B and 1C (see Table 2). Because age of acquisition affects numerous measures of L2 speech perception (e.g., Flege, 1991, 1995, 2007; Flege, Yeni-Komshian & Liu, 1999; Perani, Paulesu, Galles, Dupoux, Dehaene, Bettinardi, Cappa, Fazio & Mehler, 1998; Silverberg & Samuel, 2004; MacWhinney, 2005), it may similarly affect the development and application of an L2 processing bias.

Second, the participants tested in 2B were not currently immersed in their L2. Because L2 immersion experience can alter various cognitive and linguistic processes (e.g., Chang, 2012, 2013; Linck, Kroll & Sunderman, 2009; DeKeyser, 2010; Tokowicz, Michael & Kroll, 2004; Sunderman & Kroll, 2009; Hernandez, Li & MacWhinney, 2005), immersion may also affect the development and application of an L2 processing bias.

Experiment 2A first tested Mandarin-L1 speakers in their L1 to confirm that Mandarin elicits a V-bias during word reconstruction. Experiment 2A additionally allowed for an examination into whether Wiener and Turnbull's (2016) results were affected by the nonwords' syllable structure (e.g., lack/presence of a nasal coda) or participants' vowel response types (e.g., responding with or without a nasal coda). Experiment 2B tested English-L1 Mandarin-L2 learners to examine whether a non-native V-bias emerges in native speakers of a language that elicits a C-bias (English) despite limited L2 input and a relatively late age of acquisition.

Experiment 2A: reconstruction in Mandarin as an L1

Method

Participants

Twenty-four native Mandarin speakers (12 male; 12 female; mean age = 26.1; *SD* = 3.3) from Mainland China participated in Experiment 2A. All participants had normal hearing and speech, had completed up to high school in China, and were currently studying at an American university. While participants came from different parts of China, all participants reported Mandarin as the only Chinese dialect spoken or understood.

Materials

Sixty-four CV and CVV nonwords taken from Wiener and Turnbull's (2016) study were used as stimuli (see Supplementary Materials for stimuli and all possible changes). Each nonword could be turned into a real Mandarin word by changing the consonant, vowel, or tone. Unlike van Ooijen's (1996) English stimuli used in Experiment 1, which

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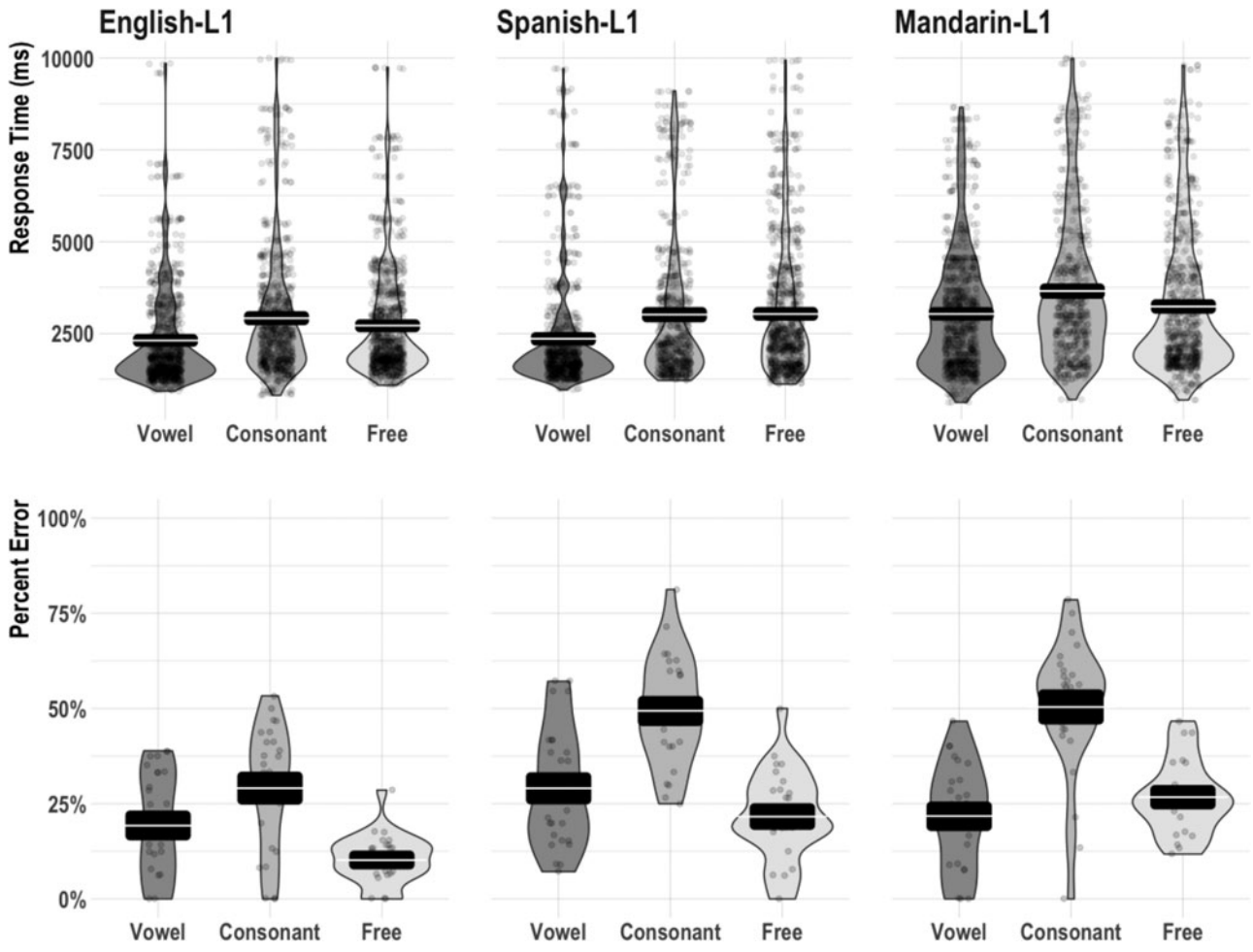


Fig. 1. Experiment 1 mean correct response times (ms) and percent error. Black box indicates 95% confidence interval. White line within interval indicates condition mean.

counterbalanced the position of the consonant/vowel change, the Mandarin stimuli used in Experiment 2 always contained a potential consonant change before a potential vowel change. An additional 32 CVN items containing a nasal coda were treated as fillers along with 12 practice items. The stimuli were recorded by a phonetically trained female native speaker of Beijing Mandarin following the same recording procedure outlined in Experiment 1 with the order of consonant, vowel, and tone counterbalanced. To ensure that the pronunciation was intelligible to participants, three speakers of Mandarin and another mutually non-intelligible Chinese dialect (Cantonese, Southern Min, Shanghai) were asked to identify the syllable and tone for all 64 nonwords. All participants identified the stimuli with 100% accuracy.

The 64 nonwords were randomly divided into four groups of 16. These groups were rotated across the four change conditions, resulting in a within-subject design identical to that used in Experiment 1.

Procedure

The procedure followed that of Experiment 1 with the addition of the tone change condition. Instructions were given in Mandarin. The Mandarin words for initial and final (rather than consonant and vowel) were used in the instructions, as these terms were more familiar to native speakers. For this reason, participants were not specifically instructed whether the addition of a nasal counted as a correct vowel change (e.g., changing *le3* to *leng3*). These trials involving CV(V)N changes were not analyzed as test items and removed from further analysis (10%). For the same reason, CVN words were not analyzed as test items but considered as fillers.

Results and discussion

Oral responses were transcribed by two native Mandarin speakers. Roughly 5% of responses were removed due to timeout errors, false alarm responses or lack of transcriber agreement. The remaining responses were scored as correct or incorrect changes. Because nearly all trials allowed for multiple answers, any response that involved the appropriate change was scored as correct. Changes that did not follow the instructions, or changes involving multiple speech sounds, were scored as incorrect. Table 1 presents mean error rates and mean correct response times for the four conditions. To test whether Mandarin-L1 participants' error rates and correct response times were statistically different across conditions, mixed effects regression models were built in R. The logistic regression model included change condition contrast coded with vowel as the reference level allowing for three planned contrasts: vowel-consonant, vowel-tone, vowel-free. Syllable type (CV or CVV) was included as a sum

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coded variable. Random by-participant and by-item intercepts and random slopes for condition were included. R formula: accuracy ~ condition + syllable type +(1|subject) + (condition|item). The linear regression model included the same variables and effects structure but tested correct response times. R formula: log RT ~ condition + syllable type +(1|subject) + (condition|item).

Vowel response accuracy was significantly lower across all three comparisons: vowel to consonant ($\beta = 0.87$, $SE = 0.15$, $z = 5.66$, $p < .001$); vowel to tone ($\beta = 2.03$, $SE = 0.17$, $z = 11.36$, $p < .001$); vowel to free ($\beta = 2.06$, $SE = 0.18$, $z = 11.51$, $p < .001$). CV/CVV syllable type did not affect overall accuracy ($\beta = -0.06$, $SE = 0.30$, $z = -0.22$, $p = .82$).

Vowel response times were significantly slower across all three comparisons: vowel to consonant ($\beta = -0.12$, $SE = 0.03$, $t = -3.15$, $p < .01$); vowel to tone ($\beta = -0.66$, $SE = 0.03$, $t = -18.14$, $p < .001$); vowel to free ($\beta = -0.58$, $SE = 0.04$, $t = -16.12$, $p < .001$). CV/CVV syllable type did not affect response times ($\beta = 0.14$, $SE = 0.11$, $t = 1.30$, $p = .21$).

Given the free choice, participants changed vowels (2,515 ms) slower than tones (2,028 ms) ($\beta = -0.21$, $SE = 0.05$, $t = -3.63$, $p < .01$) but changed vowels and consonants (2,912 ms) with similar response times ($\beta = -0.10$, $SE = 0.08$, $t = -1.31$, $p = .39$). Participants made significantly fewer vowel changes (12%) than consonant changes (27%) ($\chi^2(1) = 19.4$, $p < .001$) and fewer vowel changes than tone changes (61%) ($\chi^2(1) = 123.5$, $p < .001$).

The results of Experiment 2A confirmed that native Mandarin speakers demonstrate a V-bias during lexical processing: consonant changes were responded to faster and more accurately than vowel changes. These results were not due to listeners having perceived vowels and tones as perceptually similar information: the two conditions were responded to with statistically different response times and accuracies (e.g., Fu, Zheng, Shannon & Soli, 1998; McLoughlin, 2010; Tong et al., 2008; Zeng & Mattys, 2017). Furthermore, after removing the CV(V)N stimuli and all vowel changes involving a nasal, as well as testing whether CV or CVV syllable type affected the results, Wiener and Turnbull's (2016) original finding was replicated: Mandarin-L1 listeners changed consonants faster and more accurately than they changed vowels.

Experiment 2B next tested whether L1 speakers of a C-bias eliciting language (English) demonstrate a similar V-bias in their L2 (Mandarin) despite a relatively late age of acquisition and ongoing, non-immersion L2 classroom input.

Experiment 2B: reconstruction in Mandarin as an L2 (English-L1)

Method

Participants

Twenty-four native English speakers participated in Experiment 2B. All participants had normal hearing and speech, had completed a minimum of three years of Mandarin language instruction at the university level and were currently studying advanced Mandarin at an American university at the time of testing. No participant spoke an additional language fluently. None of the participants had previously lived or studied abroad in a Mandarin-speaking environment. See Table 2 for additional participant information.

Materials and procedure

The materials were identical to those of Experiment 2A. To ensure that the Mandarin-L2 speakers were familiar with the potential consonant, vowel, and tone change words, three additional Mandarin-L2 speakers (drawn from the same classroom population as the participants in the experiment) were asked to define the 192 words that could potentially be created. Since spoken Mandarin is highly homophonous and nearly all items resulted in multiple changes, high frequency Chinese characters of the potential words were shown to the learners. All three speakers correctly read aloud and defined the words with over 95% accuracy.

The procedure was identical to that of Experiment 2A with the instructions given in both English and Mandarin. In the English instructions, the words for consonant and vowel were used, whereas in the Mandarin instructions the words for initial and final were used (i.e., the terminology used in L2 learners' textbooks). Thus the Mandarin-L2 speakers, like the Mandarin-L1 speakers tested in Experiment 2A, were not specifically instructed whether the addition of a nasal counted as a correct vowel change. For this reason, vowel changes involving a nasal (11%) were removed from further analysis.

Results and discussion

Oral responses were transcribed by one non-native and two native Mandarin speakers.

Roughly 9% of responses were removed due to timeout errors, false alarm responses or a lack of transcriber agreement. The remaining responses were scored as correct or incorrect following the procedure outlined in Experiment 2A. Table 1 presents mean error rates and mean correct response times for the four conditions. To test whether Mandarin-L2 participants' error rates and correct response times were statistically different across conditions, mixed effect models were built identical to those outlined in Experiment 2A.

Vowel accuracy was significantly lower than free choice accuracy ($\beta = 1.78$, $SE = 0.37$, $z = 4.73$, $p < .001$) and tone accuracy ($\beta = 2.71$, $SE = 0.41$, $z = 6.52$, $p < .001$). Vowel accuracy was similar to consonant accuracy ($\beta = 0.47$, $SE = 0.36$, $z = 1.27$, $p = .20$). CV/CVV syllable type did not affect accuracy ($\beta = -0.35$, $SE = 0.27$, $z = -1.26$, $p = .20$).

Vowel response times were significantly slower across all three comparisons: vowel to consonant ($\beta = -0.16$, $SE = 0.07$, $t = -2.26$, $p = .04$); vowel to tone ($\beta = -0.58$, $SE = 0.06$, $t = -8.91$, $p < .001$); vowel to free ($\beta = -0.34$, $SE = 0.06$, $t = -5.15$, $p < .001$). CV/CVV syllable type did not affect response times ($\beta = 0.01$, $SE = 0.04$, $t = 0.44$, $p = .90$).

Given the free choice, participants changed vowels slower (4,349 ms) than they changed tones (2,863 ms) ($\beta = -0.40$, $SE = 0.12$, $t = -3.16$, $p < .01$), but changed vowels and consonants (3,710 ms) at similar speeds ($\beta = 0.19$, $SE = 0.14$, $t = 1.39$, $p = .34$). Participants made fewer vowel changes (7%) than consonant changes (20%) ($\chi^2(1) = 12.0$, $p < .001$) and fewer vowel changes than tone changes (73%) ($\chi^2(1) = 96.1$, $p < .001$).

Experiment 2B established that Mandarin-L2 speakers demonstrate a V-bias during Mandarin lexical processing: consonants were changed faster than vowels. When given the free choice, participants made fewer vowel changes than consonant changes. These results, like the Mandarin-L1 speakers' results in Experiment 2A, were not due to L2 listeners conflating vowel and tone information; accuracy and response times for the vowel and tone conditions were statistically different, supporting the claim that advanced Mandarin-L2 learners perceive the two cues as perceptually dissimilar information (e.g., Wang, Sereno, Jongman & Hirsch, 2003; Shen & Froud, 2016).

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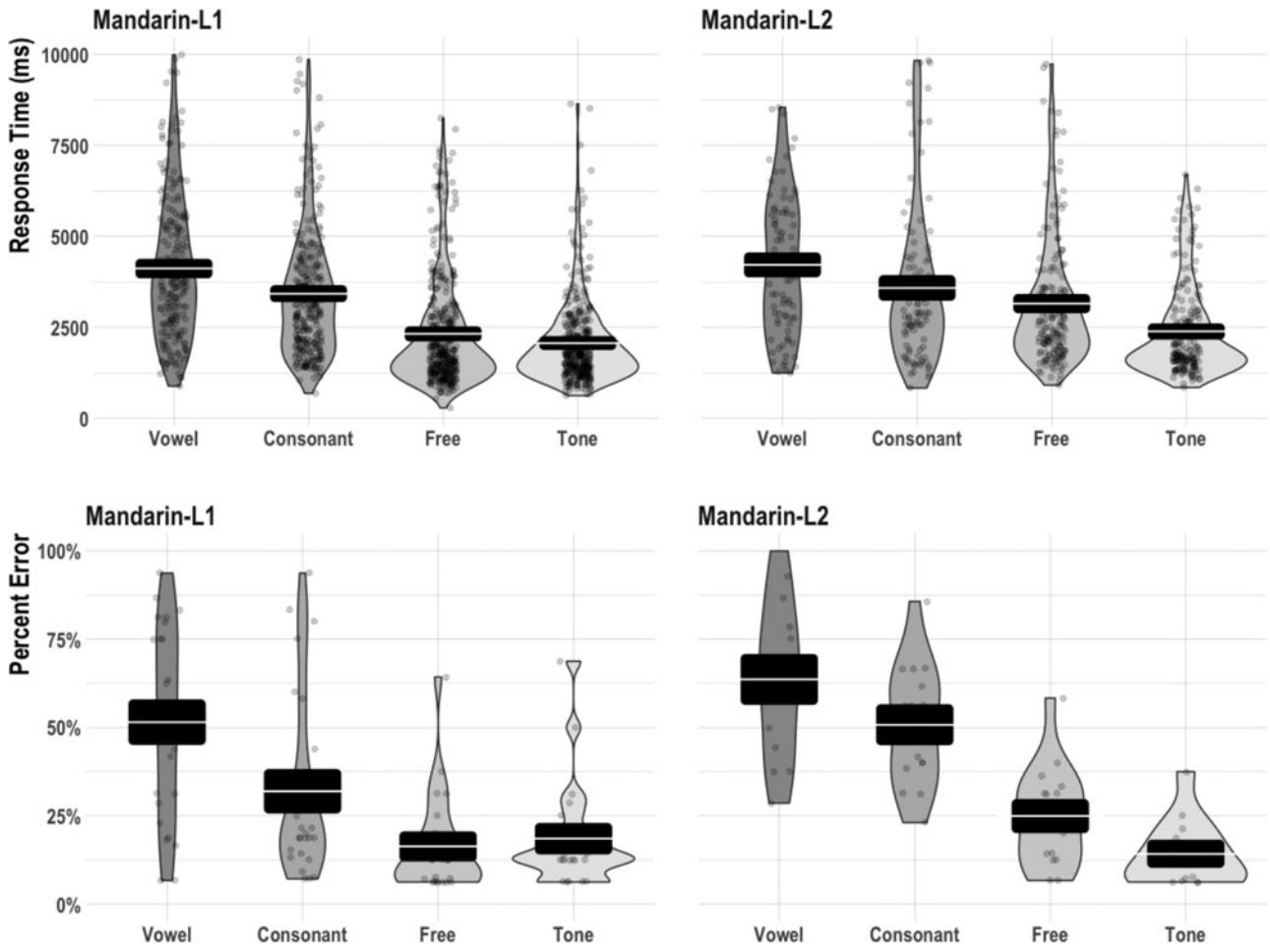


Fig. 2. Experiment 2 mean correct response times (ms) and percent error. Black box indicates 95% confidence interval. White line within interval indicates condition mean.

Summary of Experiment 2 – Mandarin reconstruction

Figure 2 plots the results of Experiment 2 using the same visualization method as Figure 1. This figure illustrates that both Mandarin-L1 and Mandarin-L2 listeners demonstrated a similar V-bias during word reconstruction by changing consonants significantly faster than vowels. Additionally, both groups were, on average, more accurate at changing consonants than vowels. This difference, however, was statistically significant only for Mandarin-L1 speakers.

The results from Experiment 2 corroborate the results from Experiment 1: phonological biases that are applied in an L2 may differ from those applied in a listener's L1 if the language demands it. Importantly, a non-native phonological bias can emerge even in adult listeners who acquire their L2 at a relatively late age and receive limited, non-immersion L2 input.

General discussion

This paper set out to investigate whether adults who speak a non-native language exhibit a lexically related processing bias in their L2, and, if so, whether such a bias is the result of L1 transfer or the phonological and lexical features of the stimuli being processed. To answer these questions, two word reconstruction experiments were carried out. In Experiment 1, English-L1, Spanish-L1, and Mandarin-L1 speakers demonstrated a C-bias in English: vowels were changed faster than consonants and vowels were changed significantly (Spanish-L1 and Mandarin-L1 groups) or marginally (English-L1 group) more accurately than consonants. This observed English-L2 C-bias was therefore similar to Spanish-L1 speakers' previously reported C-bias (Cutler et al., 2000) and different from Mandarin-L1 speakers' previously reported V-bias (Wiener & Turnbull, 2016).

In Experiment 2, Mandarin-L1 and English-L1 speakers demonstrated a V-bias in Mandarin; both groups changed consonants faster than vowels. Mandarin-L1 listeners also changed consonants significantly more accurately than vowels. This V-bias was observed in both L1 and L2 speakers when tested only on CV(V) syllables (i.e., after removing Wiener and Turnbull's (2016) problematic items with nasal codas), and when vowel responses involving nasal changes were removed from the analyses. Therefore, despite a relatively late age of acquisition and restricted, non-immersion L2 input, non-native Mandarin learners applied the appropriate phonological bias with nearly native-like efficiency. This pattern of results from Experiment 2B suggests that the observed L2 processing bias may have already emerged prior to learners developing a sizeable lexicon, as may be the case for children acquiring their L1 (e.g., Hochmann et al., 2011; Poltrock & Nazzi, 2015; Bouchon, Floccia, Fux, Adda-Decker & Nazzi,, 2015; Nishibayashi & Nazzi, 2016).

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Taken together, the results from Experiments 1 and 2 motivate the claim that adult L1 listeners weight consonants and vowels differently in English and Mandarin during lexical processing. Phonological biases in lexical processing are therefore language-specific (Højen & Nazzi, 2016; Floccia et al., 2014). For English-L1 Mandarin-L2 learners and Mandarin-L1 English-L2 learners, lexical processing in an L2 appears to involve adapting a native phonological bias to meet the specific demands of the language, i.e., a C-bias in English and a V-bias in Mandarin. Whereas ample research has documented how a C-bias develops and affects English speakers' lexical processing (Nazzi et al., 2016; Nazzi and Cutler, 2019), far less research has investigated how a potential V-bias emerges in Mandarin infants and to what degree such a bias affects adult Mandarin speakers' lexical processing. The present study's word reconstruction results contribute to the small but growing body of evidence documenting how Mandarin (and Cantonese) listeners exhibit a lexically related bias favoring vocalic information rather than consonantal information.

Within the developmental literature, evidence suggests that a V-bias may emerge in Mandarin-speaking children. In a word recognition study, Wewalaarachchi et al. (2017) demonstrated that Mandarin monolingual 24-month-olds were most sensitive to tone and then to vowel mispronunciations while Mandarin–English bilingual toddlers were most sensitive to vowel and then to tone mispronunciations. Crucially, both the monolingual and bilingual toddlers were least sensitive to consonant variation, suggesting children who speak a tonal language may become more biased towards vocalic information as their lexicon grows (see also Singh et al., 2015).

Evidence from Cantonese speaking adults further suggests that if indeed listeners of a tonal language develop a V-bias in childhood, such a bias can affect speech segmentation. In an artificial language study, Gómez et al. (2018) tested whether Cantonese-L1 adults used consonants or vowels (with tones) to segment speech. The authors found that Cantonese-L1 speakers were unable to use consonantal information alone; vocalic information was required for accurate segmentation. More recently, Poltrock, Chen, Kwok, Cheung, and Nazzi (2018) demonstrated that a V-bias might even extend to word learning in a tonal language. Poltrock et al. taught Cantonese-L1 speaking adults (along with Mandarin-L1 and French-L1 speaking adults) new label-object associations that differed minimally by a consonant, vowel, or tone. The Cantonese-L1 speakers showed no advantage for consonantal information of newly learned words, suggesting, at the very least, adult Cantonese-L1 listeners exhibit a dampening of a lexically related C-bias.

Thus, limited but converging evidence from word learning, word recognition, speech segmentation, and word reconstruction studies has documented that speakers of Mandarin and Cantonese are less biased towards consonantal information than speakers of non-tonal languages and potentially more biased towards vocalic information than speakers of non-tonal languages. If speakers of a tonal language do, in fact, develop a V-bias, there are at least two possible determinates of this V-bias in line with the "acoustic-phonetic hypothesis" (Floccia et al., 2014) and the "lexical hypothesis" (Keidel et al., 2007). From an acoustic-phonetic perspective, vowels carry the bulk of the lexically contrastive F0 information, which in turn may modulate their functional role (e.g., Højen & Nazzi, 2016) and cause vowels to become relatively more informative than consonants during lexical processing of a tonal language (e.g., Tong et al., 2008; Repp & Lin, 1990; Lee & Nusbaum, 1993).

From a lexical perspective, Mandarin and Cantonese – as well as many other tonal languages (see Yip, 2002) – have a relatively simple syllabic phonology in which a syllable can stand alone as a morpheme or word. This results in a corresponding lexicon in which vowels may potentially play a more critical role in lexical distinctions than consonants. Listeners of a tonal language may therefore weight vocalic information more heavily than consonantal information, since more neighbors can potentially be attained by changing a vowel than a consonant.

Given these two non-mutually exclusive hypotheses, Experiment 2's results remain partially incomplete. The Mandarin stimuli used in Experiment 2 – like that used in Wiener and Turnbull (2016) – consisted entirely of nonwords in which a consonant change always preceded a vowel change. These stimuli differed from van Ooijen's (1996) English nonword stimuli, which counterbalanced the position of the consonant and vowel change across items. It therefore remains an empirical question whether the consonant-initial Mandarin nonwords drove the present results given the potentially privileged status of the beginning of a word (e.g., Mehler, Dommergues, Frauenfelder & Segui, 1981; Connine, Blasko & Titone, 1993; Marslen-Wilson & Zwitserlood, 1989). It is hoped that future studies will make use of other experimental tasks and cross-linguistic comparisons to tease apart whether the reported effects in the present study (and other Mandarin and Cantonese studies) truly capture a V-bias or simply a weakened C-bias.

In conclusion, these word reconstruction results serve as a first step towards better understanding how adults develop and apply non-native phonological biases during L2 lexical processing. The results presented here support the claim that non-native processing biases develop as a by-product of the phonological and lexical properties of the language being processed and not solely through a transfer from native to non-native processing.

Supplementary Material. For supplementary material accompanying this paper, visit https://doi.org/10.1017/S1366728918001165

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References

Baayen RH, Davidson DJ and Bates DM (2008) Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language* **59**(4), 390–412.

Babjack DL, Cernicky B, Sobotka AJ, Basler L, Struthers D, Kisic R, Barone K and Zuccolotto AP (2015) Reducing audio stimulus presentation latencies across studies, laboratories, and hardware and operating system configurations. *Behavior Research Methods* **47**(3), 649–665.

Bates D, Maechler M, Bolker B and Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* **67**, 1–48.

Barr DJ, Levy R, Scheepers C and Tily HJ (2013) Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language* **68**(3), 255–278.

Basbøll H (2005) *The phonology of Danish*. Oxford: Oxford University Press.

Bonatti LL, Peña M, Nespor M and Mehler J (2005) Linguistic constraints on statistical computations the role of consonants and vowels in continuous speech processing. *Psychological Science* **16**, 451–459.

Bonatti LL, Peña M, Nespor M and Mehler J (2007) On consonants, vowels, chickens, and eggs. *Psychological Science* **18**(10), 924–925.

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Bosch L and Sebastián-Gallès N (2003) Simultaneous bilingualism and the perception of a language-specific vowel contrast in the first year of life. *Language and Speech* **46**, 217–243.

Bouchon C, Floccia C, Fux T, Adda-Decker M and Nazzi T (2015) Call me Alix, not Elix: vowels are more important than consonants in own-name recognition at 5 months. *Developmental Science* **18**(4), 587–598.

Cai Q and Brysbaert M (2010) SUBTLEX-CH: Chinese word and character frequencies based on film subtitles. *PloS one* **5**(6), e10729.

Chang CB (2012) Rapid and multifaceted effects of second-language learning on first- language speech production. *Journal of Phonetics* **40**(2), 249–268.

Chang CB (2013) A novelty effect in phonetic drift of the native language. *Journal of Phonetics* **41**(6), 520–533.

Connine CM, Blasko DG and Titone D (1993) Do the beginnings of spoken words have a special status in auditory word recognition? *Journal of Memory and Language* **32**, 193–210.

Connine CM, Blasko DG and Wang J (1994) Vertical similarity in spoken word recognition: Multiple lexical activation, individual differences, and the role of sentence context. *Perception & Psychophysics* **56**, 624–636.

Creel SC, Aslin RN and Tanenhaus MK (2006) Acquiring an artificial lexicon: Segment type and order information in early lexical entries. *Journal of Memory and Language* **54**, 1–19.

Cutler A (2012) *Native listening*. MIT Press.

Cutler A and Otake T (2002) Rhythmic categories in spoken-word recognition. *Journal of Memory and Language* **46**(2), 296–322.

Cutler A, Sebastián-Gallés N, Soler-Vilageliu O and van Ooijen B (2000) Constraints of vowels and consonants on lexical selection: Cross-linguistic comparisons. *Memory & Cognition* **28**, 746–755.

DeFrancis J (1986) *The Chinese language: Fact and fantasy*. University of Hawaii Press.

DeKeyser R (2010) Monitoring processes in Spanish as a second language during a study abroad program. *Foreign Language Annals* **43**(1), 80–92.

Delle Luche, C., Poltrock S, Goslin J, New B, Floccia C and Nazzi T (2014) Differential processing of consonants and vowels in the auditory modality: A cross-linguistic study. *Journal of Memory and Language* **72**, 1–15.

Duanmu S (2007) *The Phonology of Standard Chinese*. New York: Oxford University Press.

Duanmu S (2009) *Syllable Structure: The Limits of Variation*. New York: Oxford University Press.

Flege JE (1991) Perception and production: The relevance of phonetic input to L2 phonological learning. In T Heubner & C Ferguson (eds.), *Crosscurrents in second language acquisition and linguistic theories* pp. 249–289. Philadelphia, PA: John Benjamins.

Flege JE (1995) Second-language Speech Learning: Theory, Findings, and Problems. In W Strange (ed.), *Speech Perception and Linguistic Experience: Issues in Cross-language research* pp. 229–27. Timonium, MD: York Press.

Flege JE (2007) Language contact in bilingualism: Phonetic system interactions. *Laboratory Phonology* **9**, 353–382.

Flege JE, Yeni-Komshian GH and Liu S (1999) Age constraints on second-language acquisition. *Journal of Memory and Language* **41**(1), 78–104.

Floccia C, Nazzi T, Delle Luche C, Poltrock S and Goslin J (2014) English-learning one-to two-year-olds do not show a consonant bias in word learning. *Journal of Child Language* **41**(5), 1085–1114.

Fu QJ, Zeng FG, Shannon RV and Soli SD (1998) Importance of tonal envelope cues in Chinese speech recognition. *Journal of the Acoustical Society of America* **104**, 505–510.

Gandour J (1983) Tone perception in far eastern-languages. *Journal of Phonetics* **11**(2), 149–175.

Gómez DM, Mok P, Ordin M, Mehler J and Nespor M (2018) Statistical speech segmentation in tone languages: The role of lexical tones. *Language and Speech* **61**(1), 84–96.

Grønnum N (1998) Danish: illustrations of the IPA. *Journal of the International Phonetic Association* **28**, 99–105.

Havy M, Bouchon C and Nazzi T (2016) Phonetic processing when learning words: The case of bilingual infants. *International Journal of Behavioral Development* **40**(1), 41–52.

Havy M and Nazzi T (2009) Better processing of consonantal over vocalic information in word learning at 16 months of age. *Infancy* **14**, 439–456.

Havy M, Serres J and Nazzi T (2014) A consonant/vowel asymmetry in word-form processing: Evidence in childhood and in adulthood. *Language and Speech* **57**(2), 254–281.

Hernandez A, Li P and MacWhinney B (2005) The emergence of competing modules in bilingualism. *Trends in Cognitive Sciences* **9**(5), 220–225.

Ho AT (1976) The acoustic variation of Mandarin tones. *Phonetica* **33**, 353–367.

Hochmann JR, Benavides-Varela S, Nespor M and Mehler J (2011) Consonants and vowels: Different roles in early language acquisition. *Developmental Science* **14**, 1445–1458.

Højen A and Nazzi T (2016) Vowel bias in Danish word-learning: processing biases are language-specific. *Developmental Science* **19**(1), 41–49.

Keidel JL, Jenison RL, Kluender KR and Seidenberg MS (2007) Does grammar constrain statistical learning? Commentary on Bonatti, Peña, Nespor, and Mehler (2005). *Psychological Science* **18** (10), 922–923.

Kuznetsova A, Brockhoff PB and Christensen RHB (2017) lmerTest package: tests in linear mixed effects models. *Journal of Statistical Software* **82** (13).

Lee L and Nusbaum HC (1993) Processing interactions between segmental and suprasegmental information in native speakers of English and Mandarin Chinese. *Attention, Perception, & Psychophysics* **53**, 157–165.

Lenth RV (2016) Least-squares means: the R package lsmeans. *Journal of Statistical Software* **69**, 1–33.

Linck JA, Kroll JF and Sunderman G (2009) Losing access to the native language while immersed in a second language: Evidence for the role of inhibition in second-language learning. *Psychological Science* **20**(12), 1507–1515.

Mani N and Plunkett K (2010) Twelve-month-olds know their cups from their keps and tups. *Infancy* **15**(5), 445–470.

MacWhinney B (2005) A unified model of language acquisition. In J Kroll & A. De Groot (eds.), *Handbook of bilingualism: Psycholinguistic approaches* pp. 49–67. New York: Oxford University Press.

Malins JG and Joanisse MF (2010) The roles of tonal and segmental information in Mandarin spoken word recognition: An eyetracking study. *Journal of Memory and Language* **64**, 407–420.

Malins JG and Joanisse MF (2012) Setting the tone: An ERP investigation of the influences of phonological similarity on spoken word recognition in Mandarin Chinese. *Neuropsychologia* **50**, 2032–2043.

Marks EA, Moates DR, Bond ZS and Stockmal V (2002) Word reconstruction and consonant features in English and Spanish. *Linguistics* **40**, 421–438.

Marslen-Wilson WD (1990) Activation, competition, and frequency in lexical access. In GTM Altmann (ed.), *Cognitive models of speech processing: Psycholinguistic and computational perspectives* pp. 148–172. Cambridge, MA: MIT Press.

Marslen-Wilson W and Zwitserlood P (1989) Accessing spoken words: The importance of word onsets. *Journal of Experimental Psychology: Human Perception and Performance* **15**, 576–585.

Matuschek H, Kliegl R, Vasishth S, Baayen H and Bates D (2017) Balancing Type I error and power in linear mixed models. *Journal of Memory and Language* **94**, 305–315.

McLoughlin I (2010) Vowel intelligibility in Chinese. *IEEE Transactions on Audio, Speech, and Language Processing* **18**, 117–125.

McQueen JM, Norris DG and Cutler A (1994) Competition in spoken word recognition: Spotting words in other words. *Journal of Experimental Psychology: Learning, Memory & Cognition* **20**, 621–638.

McQueen JM, Norris DG and Cutler A (1999) Lexical influence in phonetic decision-making: Evidence from subcategorical mismatches. *Journal of Experimental Psychology: Human Perception & Performance* **25**, 1363–1389.

Mehler J, Dommergues JY, Frauenfelder U and Segui J (1981) The syllable's role in speech segmentation. *Journal of Verbal Learning and Verbal Behavior* **20**, 298–305.

Nazzi T (2005) Use of phonetic specificity during the acquisition of new words: Differences between consonants and vowels. *Cognition* **98**, 13–30.

Nazzi T and Bertoncini J (2009) Phonetic specificity in early lexical acquisition: New evidence from consonants in coda positions. *Language and Speech* **52**(4), 463–480.

Nazzi T and Cutler A (2019) How Consonants and Vowels Shape Spoken-Language Recognition. *Annual Review of Linguistics* **5**(1), 25–47.

https://doi.org/10.1017/S1366728918001165 Published online by Cambridge University Press

Nazzi T, Floccia C, Moquet B and Butler J (2009) Bias for consonantal information over vocalic information in 30-month-olds: Cross-linguistic evidence from French and English. *Journal of Experimental Child Psychology* **102**(4), 522–537.

Nazzi T and Poltrock S (2016) Consonant bias in the use of phonological information during lexical processing: A lifespan and cross-linguistic perspective. In MG Gaskell and J Mirkovic, J (Eds.), *Speech perception and spoken word recognition* pp. 37–54. Psychology Press.

Nazzi T, Poltrock S and Von Holzen K (2016) The developmental origins of the consonant bias in lexical processing. *Current Directions in Psychological Science* **25**(4), 291–296.

Nazzi T and New B (2007) Beyond stop consonants: Consonantal specificity in early lexical acquisition. *Cognitive Development* **22**(2), 271–279.

Nespor M, Peña M and Mehler J (2003) On the different roles of vowels and consonants in speech processing and language acquisition. *Lingue e linguaggio* **2**, 203–230.

New B, Araùjo V and Nazzi T (2008) Differential processing of consonants and vowels in lexical access through reading. *Psychological Science* **19**, 1223–1227.

Nishibayashi LL and Nazzi T (2016) Vowels, then consonants: Early bias switch in recognizing segmented word forms. *Cognition* **155**, 188–203.

Packard JL (2000) *The morphology of Chinese: A linguistic and cognitive approach*. Cambridge University Press.

Perani D, Paulesu E, Galles NS, Dupoux E, Dehaene S, Bettinardi V, Cappa SF, Fazio F and Mehler J (1998) The bilingual brain. Proficiency and age of acquisition of the second language. *Brain: A journal of neurology* **121**(10), 1841–1852.

Pharao N (2011) Plosive reduction at the group level and in the individual speaker. Paper presented at the *International Congress of Phonetic Sciences XVII* 2011, Hong Kong.

Poltrock S, Chen H, Kwok C, Cheung H and Nazzi T (2018) Adult Learning of Novel Words in a Non-native Language: Consonants, Vowels, and Tones. *Frontiers in psychology* **9**.

Poltrock S and Nazzi T (2015) Consonant/vowel asymmetry in early word form recognition. *Journal of Experimental Child Psychology* **131**, 135–148.

Psychology Software Tools, Inc. [E-Prime 2.0]. (2012) Retrieved from http://www.pstnet.com.

Quené H and Van den Bergh H (2008) Examples of mixed-effects modeling with crossed random effects and with binomial data. *Journal of Memory and Language* **59**(4), 413–425.

R Core Team (2017) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from http://www.R-project.org/.

Repp BH and Lin H-B (1990) Integration of segmental and tonal information in speech perception: a cross-linguistic study. *Journal of Phonetics* **18**, 481–495.

Samuel AG (2011) Speech perception. *Annual Review of Psychology* **62**, 49–72.

Sebastián-Gallès N, Echeverria S and Bosch L (2005) The influence of initial exposure on lexical representation: Comparing early and simultaneous bilinguals. *Journal of Memory and Language* **52**, 240–255.

Sharp DJ, Scott SK, Cutler A and Wise RJ (2005) Lexical retrieval constrained by sound structure: The role of the left inferior frontal gyrus. *Brain and Language* **92**(3), 309–319.

Shen G and Froud K (2016) Categorical perception of lexical tones by English learners of Mandarin Chinese. *The Journal of the Acoustical Society of America* **140**(6), 4396–4403.

Shillcock RC (1990) Lexical hypotheses in continuous speech. In GTM Altmann (ed.), *Cognitive models of speech processing: Psycholinguistic and computational perspectives* pp. 24–49. Cambridge, MA: MIT Press.

Silverberg S and Samuel AG (2004) The effect of age of second language acquisition on the representation and processing of second language words. *Journal of Memory and Language* **51**(3), 381–398.

Singh L, Goh HH and Wewalaarachchi TD (2015) Spoken word recognition in early childhood: comparative effects of vowel, consonant and lexical tone variation. *Cognition* **142**, 1–11.

Sunderman G and Kroll JF (2009) When study-abroad experience fails to deliver: The internal resources threshold effect. *Applied Psycholinguistics* **30**(1), 79–99.

Tokowicz N, Michael EB and Kroll JF (2004) The roles of study-abroad experience and working-memory capacity in the types of errors made during translation. *Bilingualism: Language and Cognition* **7**(3), 255–272.

Tong Y, Francis AL and Gandour JT (2008) Processing dependencies between segmental and suprasegmental features in Mandarin Chinese. *Language and Cognitive Processes* **23**, 698–708.

Toro JM, Nespor M, Mehler J and Bonatti LL (2008a) Finding words and rules in a speech stream: functional differences between vowels and consonants. *Psychological Science* **19** (2), 137–144.

Toro JM, Shukla M, Nespor M and Endress AD (2008b) The quest for generalizations over consonants: asymmetries between consonants and vowels are not the by-product of acoustic differences. *Perception & Psychophysics* **70** (8), 1515–1525.

van Ooijen B (1996) Vowel mutability and lexical selection in English: Evidence from a word reconstruction task. *Memory & Cognition* **24**, 573–583.

Vitevitch MS and Luce PA (1998) When words compete: levels of processing in perception of spoken words. *Psychological Science* **9**, 325–329.

Vitevitch MS and Luce PA (1999) Probabilistic phonotactics and neighborhood activation in spoken word recognition. *Journal of Memory and Language* **40**, 374–408.

Wang Y, Sereno JA, Jongman A and Hirsch J (2003) fMRI evidence for cortical modification during learning of Mandarin lexical tone. *Journal of Cognitive Neuroscience* **15**(7), 1019–1027.

Wewalaarachchi TD, Wong LH and Singh L (2017) Vowels, consonants, and lexical tones: Sensitivity to phonological variation in monolingual Mandarin and bilingual English–Mandarin toddlers. *Journal of Experimental Child Psychology* **159**, 16–33.

Wiener S and Ito K (2015) Do syllable-specific tonal probabilities guide lexical access? Evidence from Mandarin, Shanghai and Cantonese speakers. *Language, Cognition and Neuroscience* **30**, 1048–1060.

Wiener S and Turnbull R (2016) Constraints of tones, vowels and consonants on lexical selection in Mandarin Chinese. *Language and Speech* **59**, 59–82.

Xu Y (1999) Effects of tone and focus on the formation and alignment of F0 contours. *Journal of Phonetics* **27**, 55–105.

Yip M (2002) *Tone*. Cambridge University Press.

Zeng B and Mattys SL (2017) Separability of tones and rhymes in Chinese speech perception: Evidence from perceptual migrations. *Language and Speech* **60**(4), 562–570.

Zhao J, Guo J, Zhou F and Shu H (2011) Time course of Chinese monosyllabic spoken word recognition: Evidence from ERP analyes. *Neuropsychologia* **49**, 1761–1770.

Zhou X and Marslen-Wilson W (1994) Words, morphemes and syllables in the Chinese mental lexicon. *Language and Cognitive Processes* **9**, 393–422.

Zhou X and Marslen-Wilson W (1995) Morphological structure in the Chinese mental lexicon. *Language and Cognitive Processes* **10**, 545–600.

https://doi.org/10.1017/S1366728918001165 Published online by Cambridge University Press