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Immediate Cross-Language Transfer of Novel Articulatory Plans in Bilingual Speech

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Current models of second language (L2) acquisition focus on interactions with a first language (L1) at the level of speech sound targets. In multilinguals, the degree of interaction between the articulatory plans that guide speech in each language remains unclear. Here, we directly address this question in bilingual speakers. We use a sensorimotor adaptation paradigm to drive the acquisition of novel articulatory plans for speech in one language and then measure the extent to which these new motor plans influence articulatory plans in the speaker's other language. Twenty L1-French, L2-English bilinguals adapted their speech production to a real-time alteration of vowel sounds. In one session, the adaptation was acquired during French sentence production; in a second session, the adaptation was acquired during English sentence production. In each session, cross-language transfer of these novel articulatory plans for speech was assessed using a transfer task that involved the production of French and English words with heavily noise-masked auditory feedback. Sensorimotor adaptation that countered the vowel sound alteration was observed in both French and English. Regardless of the linguistic context in which the adaptation was acquired, the adaptation transferred to the production of words in both languages. The amount of transfer did not depend on whether the adaptation was acquired in the participant's L1 or L2. In a second experiment, the result was replicated with 20 L1-English, L2-French speakers. The experiments support the idea that, in bilinguals, the interaction between L1 and L2 articulatory motor plans is rapid and bidirectional.

Public Significance Statement
This study examined how the motor plans that guide speech production in different languages interact in bilinguals. English–French bilinguals from Canada learned new speech movements (articulatory plans) in English or French. Next, the application (transfer) of these new speech patterns to their other language was assessed. Despite proficiency differences between languages, bilingual speakers readily transferred new speech movements from one language to the other. The results provide insight into the organization of articulatory plans in bilingual speakers.

Keywords: phonetics, bilinguals, speech production, articulation, sensorimotor adaptation

Learning to speak a second language (L2) is a demanding task; it involves not only learning the grammar and vocabulary of the L2, but also the phonological categories and their associated acoustic and articulatory representations. While learners of L2 strive to achieve accurate pronunciation in their L2, many who learn a new language after childhood produce accented L2 speech, even after decades of L2 use and immersion. Studies have revealed a number of predictors of L2 accent strength, such as the age at which a person began L2 learning and the amount of continued first language (L1) use (Piske et al., 2001). But much remains to be understood about how knowledge of two languages influences articulation during speech.

One key factor that appears to contribute to difficulties in L2 speech learning later in life (and the presence of a noticeable accent) is the assimilation of L2 speech sound categories into related—but not identical—speech sound categories from the speaker's L1.

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In this case, the acoustic targets of L2 speech become biased toward similar targets in L1, and, as a result, L2 speech sounds are produced inaccurately. This explanation is supported by considerable evidence from studies of L2 speech perception (Flege, 1987; Flege et al., 1997; Meador et al., 2000) and is a central mechanism to explain the difficulty faced by L2 learners in models of L2 acquisition (e.g., the speech learning model [SLM]; Flege, 1995 or the perceptual assimilation model of L2 speech learning; Best and Tyler, 2007).

Another factor that may contribute to difficulties in L2 speech learning is an interaction with the speaker's L1 at the level of articulatory plans for speech. Just as L2 learning requires the acquisition of novel auditory perceptual categories that may be influenced by similar, but not identical, perceptual representations in their L1, L2 learning also requires the acquisition of novel articulatory plans that may be influenced by existing L1 plans. In L2 learners, interactions between articulatory motor representations seem to contribute to inaccurate L2 productions. For example, improvements in the perception of L2 phonemes following L2 perceptual training do not always result in corresponding production improvements (Bradlow et al., 1997; Rochet, 1995). The perception of L2 speech is not enough on its own to explain the presence of an accent.

To date, interference between languages at the level of articulation has only been indirectly demonstrated. This work suggests that the degree of cross-language interference between articulatory representations may depend on the linguistic history of the speaker. For example, Alario et al. (2010) used the syllable frequency effect (the observation that more commonly used syllables are produced faster) to provide evidence for an interaction between L1 and L2 syllabic motor plans in late French–Spanish bilinguals, but not in early bilinguals. Other work also suggests that bilinguals can produce the same phoneme differently depending on the language they are speaking. Caramazza et al. (1973) examined Voice Onset Time in English–French bilinguals and came to the conclusion that there was little phonological interference during production, especially from L2 to L1. This finding was supported in later work that also examined Voice Onset Time as a measure of L1–L2 interactions (Antoniou et al., 2011).

More generally, units of language can act as a contextual cue allowing users to acquire different articulatory plans for the same phoneme category in some circumstances (Rochet-Capellan & Ostry, 2011). Taken together, this work suggests that some bilinguals might be able to acquire and maintain language-specific articulatory motor plans. The current study directly tests this question using sensorimotor adaptation to real-time alterations of auditory feedback during speech.

Alterations of auditory feedback during speech production allow for the direct manipulation and measurement of articulatory plans for phonemes and syllables (Houde & Jordan, 1998; Niziolek & Guenther, 2013; Purcell & Munhall, 2006; Rochet-Capellan & Ostry, 2011). In this paradigm, key acoustic features of vowel sounds (e.g., formant frequencies) are altered in real-time as participants speak and are presented back to the speaker via headphones. The alteration induces a mismatch between the speaker's predicted and actual acoustic feedback. Such a mismatch has been demonstrated to induce, over many trials, an adaptive change (or sensorimotor adaptation) in the way participants articulate vowels to counter the disturbance. These compensatory changes in vowel production are implicit and persist after the feedback alteration is removed (Kim & Max, 2021; Lametti et al., 2020; Munhall et al., 2009). The existence of such aftereffects indicates that the adaptation has updated the stored relationship between articulatory plans and acoustic representation of speech sounds (Houde & Jordan, 1998; Jones & Munhall, 2005; Lametti et al., 2014, 2018; Shiller et al., 2009).

To date, two notable studies have used altered auditory feedback to examine the relationship between language-specific phonological representations and adaptation, but cross-language interactions in speech motor planning were not directly assessed (Mitsuya et al., 2011, 2013). Furthermore, studies involving manipulations of auditory feedback during speech have almost exclusively used simple, isolated productions such as repetitions of a single word (e.g., head). The use of simple productions allows for the precise measurement and manipulation of speech motor planning and control, but word repetition requires little linguistic processing above the level of lexical access.

We recently demonstrated that altered auditory feedback can be used to study adaptive changes in articulation during the production of grammatically complex sentences (Lametti et al., 2018). In this work, participants produced a subset of the Harvard sentences (a phonetically balanced corpus of English sentences; Rothauser, 1969), while the first (F1) and second (F2) formant frequency of vowels was uniformly altered in real-time. At the level of sentences, adaptive changes in F1 and F2 production were observed that precisely countered the vowel distortion. Additionally, a transfer task, in which participants produced words with varying vowel sounds with noise-masked auditory feedback demonstrated that these changes in articulation were compensatory across the full range of vowels and did not impact other properties of speech such as pitch. The result could not be explained by a simple, global articulatory change; it suggested that adaptation to an alteration of all vowel sounds is driven by changes to the phoneme-specific articulatory plans that guide speech. These changes can be applied broadly across different levels of production (i.e., from sentences to single-syllable productions).

In the current study, we use a multilingual extension of this sentence-level altered auditory feedback paradigm to test the degree to which articulatory motor plans acquired in L1 remain segregated from L2 and vice versa. In two different groups of proficient bilinguals, we apply altered auditory feedback during sentence production. The alteration drives a change in the relationship between speech sounds and articulatory plans in one language; we then examine whether this novel relationship is applied equally to the production of vowels in both of the speaker's languages.

Method

Participants

We recruited 40 bilinguals between the ages of 18 and 65 that had no reported history of hearing or speech disorders. Twenty L1-French, L2-English participants were recruited in Montreal, Quebec, and tested at the Université de Montréal. These participants took part in Experiment 1. Twenty L1-English, L2-French participants were recruited in Wolfville, Nova Scotia, and tested at Acadia University. These participants took part in Experiment 2. Group sizes of 20 were selected based on Lametti et al. (2018), in which sensorimotor adaptation in response to altered auditory feedback was observed during the production of English sentences with group sizes of 10. Participants were asked to indicate their biological sex in a free response box. In Experiment 1, eight of the participants indicated they were male and 12 indicated they were female. In Experiment 2, seven of the participants indicated they were male and 13 indicated they were female. The experiments were approved by Research Ethics Committees at the Université de Montréal and Acadia University.

Before the start of the study, participants completed a short questionnaire adapted from the Language Experience and Proficiency Questionnaire (Marian et al., 2007). Participants indicated on a scale from 1 (*beginner*) to 10 (*expert*) their perceived proficiency in English and French. Using the same scale, they also rated their ability to write, speak, and read in English and French. Finally, they indicated the age at which they began to learn English and French.

In both experiments, participants varied in their L2 proficiency, but all reported a moderate or advanced level of reading, writing, and speaking in their L2. In Experiment 1 involving L1-French speakers, on a scale from 1 (*beginner*) to 10 (*expert*), reported measures of English (L2) proficiency ranged from 5 to 9 out of 10 and averaged 7.68 (1.0 *SD*). The mean reported age of first exposure to English was 7.75 years (3.68 *SD*). In Experiment 2 involving L1-English speakers, reported measures of French (L2) proficiency ranged from 6 to 10 out of 10 and averaged 7.5 (1.1 *SD*). The mean reported age of first exposure to French was 6.15 years (3.04 *SD*).

Experimental Setup

The experimental setup was identical at both testing sites. Participants sat in front of a computer screen placed at eye level. They spoke into a head-mounted microphone (Shure, WH20) and wore headphones (Sennheiser, HD 280 Pro). Speech was recorded at 16,000 Hz via a computer running Matlab (MathWorks).

Speech Stimuli

For the main experimental task, participants read aloud sentences in either English or French drawn from the Harvard Sentences (Rothauser, 1969), a corpus of phonetically balanced English sentences. Fifty English sentences and their French translations were selected such that the average sentence length was matched between the two languages. While the 50 French sentences were direct translations and hence not designed from the beginning to be phonetically balanced, they include a good representation of phonemes spanning the entire vowel space. See Tables A1 and A2 for the sentences used in the study.

In a second (*Transfer*) task, participants read aloud 16 monosyllabic words (Table 1). Eight of the words were French (*eau*, *eux*, *pâte*, *patte*, *pis*, *pote*, *sept*, *toute*) and the remaining words were English (*bid*, *hood*, *pat*, *pea*, *pot*, *putt*, *set*, *toot*). The eight words in English and French were selected because they contain vowels that span the acoustic and articulatory workspace in the two respective languages. The words were presented on screen in a pseudorandom order. To promote code-switching, they were preceded by either "Say" if the word was English (e.g., Say: "pat") or "Dis" if the word was French (e.g., Dis: « *patte* »). Prior work suggests that such code-switching between Canadian French and English has little impact on key properties of speech acoustics such as formant frequencies and pitch (Muldner et al., 2019).

Table 1

The Eight French Words (Left Panel) and Eight English Words (Right Panel) Read Aloud by Participants During the Transfer Task

French Words	IPA	English words	IPA
pis	/pi/	pea	/pi/
eux	/ø/	bid	/bɪd/
sept	/sɛt/	set	/sɛt/
patte	/pat/	pat	/pæt/
pâte	/pɑt/	pot	/pɑt/
pote	/pɔt/	putt	/pʌt/
eau	/o/	hood	/hʊd/
toute	/tut/	toot	/tut/

Note. The IPA transcription of each word is shown to the right of each orthographic representation. IPA = International Phonetic Alphabet.

General Procedure

Each of the 40 participants in the study came to the lab for two, 90-min testing sessions that were separated by at least 1 week. In one session, participants experienced altered auditory feedback to induce an articulatory adaptation during the production of English sentences, after which transfer of the adaptation to the production of both English and French words was measured. In the second session, participants experienced altered auditory feedback to induce an articulatory adaptation during the production of French sentences, followed again by an examination of transfer to both English and French words. The order of the sessions was counterbalanced across participants.

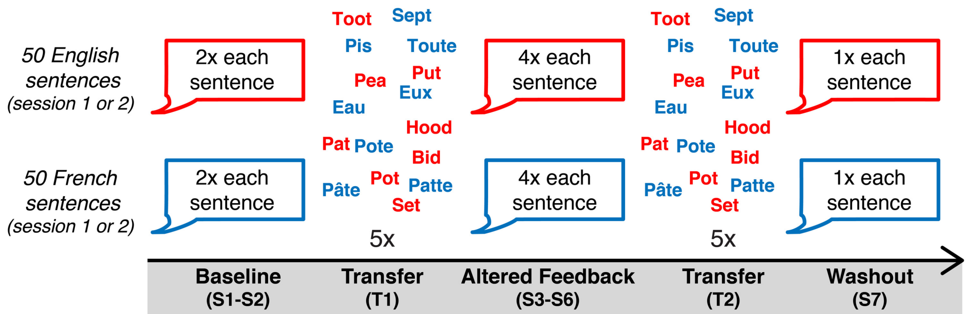
Following Lametti et al. (2018), testing sessions were divided into seven blocks in which each of the 50 sentences was produced once, in a random order (see Figure 1). During the first two sentence blocks (S1 and S2), participants experienced normal auditory feedback. During sentence blocks (S3–S6), participants experienced altered auditory feedback (see Altered Auditory Feedback section). The final sentence block (S7) was completed with normal auditory feedback to "washout" changes in production associated with altered feedback.

Participants also produced isolated words during two transfer blocks (T1 and T2). Transfer blocks occurred before and after altered auditory feedback associated with sentence production (before S3 and after S6). Each of the 16 transfer words (eight French, eight English) was presented five times in a random order. During the transfer blocks, speech feedback was replaced with noise that scaled in amplitude to match the amplitude envelope of the speech signal. Thus, auditory feedback was heavily masked during the transfer blocks. Masked feedback was used to allow for more direct measurement of feedforward changes in articulation associated with altered auditory feedback. The transfer blocks also served to measure the extent to which feedforward changes in vowel production acquired in the context of one language would be applied to productions in the speaker's other language.

Altered Auditory Feedback

During sentence production, the speech signal was mixed with speech-shaped masking noise and presented back to participants in near-real-time via the headphones using the MATLAB-based program Audapter (Cai et al., 2008). In both testing sessions, an articulatory adaptation was induced by altering the F1 and F2

Figure 1
Experimental Design



Note. L1-French L2-English and L1-English L2-French bilinguals experienced two counterbalanced sessions in which they produced blocks of 50 sentences in English or French. Following baseline production (S1 and S2) in which each sentence was produced 2×, they produced each sentence 4× times under conditions of altered F1–F2 auditory feedback (S3–S6). Altered feedback was followed by the production of each sentence with normal auditory feedback to "washout" adaptation (S7). A transfer task involving the noise-masked production of 16 words, eight in English (red words) and eight in French (blue words), occurred before and after altered auditory feedback (T1 and T2). L1 = first language; L2 = second language; S1 = first sentence block; S2 = second sentence block; S3 = third sentence block; S4 = fourth sentence block; S5 = fifth sentence block; S6 = sixth sentence block; S7 = seventh sentence block; F1 = first formant frequency; F2 = second formant frequency; T1 = first transfer block; T2 = second transfer block. See the online article for the color version of this figure.

frequencies of all vowels that participants heard themselves producing. Following Lametti et al. (2018), we applied a 49.5 mel decrease to F1 and a 49.5 mel increase to F2 for a total change of 70 mels in the F1/F2 vowel space. This alteration was increased linearly over the first 25 trials of the third sentence block (S3) and was then held at a constant 70 mels until the end of the sixth sentence block (S6; see Figure 1).

Acoustic Analysis

The software package Praat was used for the analysis of speech acoustics (Boersma & Weenink, 2023). For sentences, Praat's autocorrelation method removed pauses and unvoiced consonants from the acoustic signal, leaving the vocalized portions of speech, which largely consist of vowels. Measures of F1 and F2 frequency were then obtained from these segments using linear predictive coding (LPC). The median F1 and F2 value was found for each sentence. For the monosyllabic words produced during the transfer task, LPC was used to compute average F1 and F2 values over a 25 ms (400 samples) window at the center of each vowel (located visually on the basis of the acoustic waveform).

Data Analysis

To assess adaptation related to altered auditory feedback, changes in F1 and F2 frequency associated with sensorimotor adaptation (S6−S2), aftereffects of adaptation (S7−S2), and transfer of adaptation (T2−T1) were projected onto a vector in F1–F2 space that perfectly opposed the direction of the applied change in the sound of the voice. Following Niziolek and Guenther (2013) and Lametti et al. (2018), the angular difference between the inverse of the vector representing the feedback shift and the vector representing production change in F1–F2 space was found. The cosine of this difference was then multiplied by the magnitude of the production change. This resulted in a single value that represented the degree to which the observed change in F1 and F2 countered the feedback alteration. Compensation for altered auditory feedback was compared between languages using paired sample t tests. Transfer of compensation for altered auditory feedback was compared between languages using repeated measures analysis of variance (rANOVA) and paired sample t tests. Single-sample directional t tests were used to assess whether compensation and transfer were greater than zero. The significance level for statistical tests was 0.05. p Values were corrected for multiple comparisons using the false discovery rate correction (Benjamini & Hochberg, 1995).

Transparency and Openness

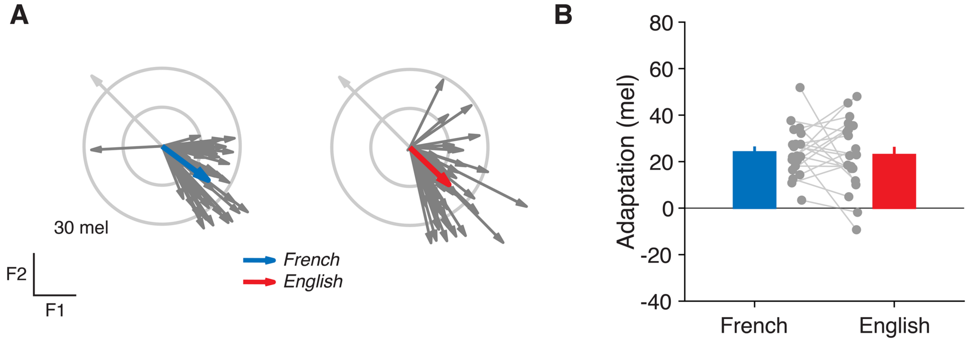
Unprocessed experimental data and the corresponding analysis scripts are available from the corresponding author upon request. Processed data (e.g., participant means) and a Matlab script to generate the bar plots in the paper are available at the Open Science Framework: https://osf.io/gvf32/.

Results

The aim of the study was to induce an adaptation of speech production in either L1 or L2 in French–English bilinguals, and then examine the extent to which this new sensorimotor map for speech would be applied across languages.

The vectors in Figure 2A show how F1 and F2 changed in response to altered auditory feedback during the production of sentences in French (left vector plot) and English (right vector plot). Learned changes in production countered the induced change in the sound of the voice (the light gray arrows depict the direction of the feedback alteration). These changes are quantified in Figure 2B, which shows the average amount of adaptation to the feedback alteration during the production of sentences in French

Figure 2
Experiment 1, Adaptation



Note. (A) The gray vectors show the average F1–F2 change for each of the 50 French (left) and English (right) sentences during altered auditory feedback. The blue and red vectors show the average F1–F2 change across sentences. (B) The bars depict F1–F2 change during French (blue) and English (red) sentence production in direct compensation for the formant alteration. The gray dots depict individual data points; the gray lines link data for each participant. All error bars are ± 1 *SE*. F1 = first formant frequency; F2 = second formant frequency. See the online article for the color version of this figure.

(blue bars) and English (red bars). Specifically, the figure shows the amount of change in F1/F2 space (S6−S2) that directly countered the +F1/−F2 feedback alteration. Adaptation averaged 34.45% (24.11 mels) during the production of French sentences and 32.79% (22.95 mels) during the production of English sentences. In both cases, adaptation was significantly greater than zero, directional one-sample t tests—French, $t(19) = 9.98$, $p < .001$, Cohen's $d = 4.58$; English, $t(19) = 6.74$, $p < .001$, Cohen's $d = 3.09$. There was no difference in the amount of adaptation associated with the production of French (L1) or English (L2) sentences, paired-sample t test, $t(19) = 0.3$, $p = .76$, Cohen's $d = 0.14$. Thus, despite the difference in proficiency between speakers' L1 and L2, articulatory adaptation in the two languages did not differ.

The vectors in Figure 3A show the transfer of the adaptation acquired during French (*train French*) and English (*train English*) sentence production to the production of monosyllabic words in both French and English. The mean amount of transfer is quantified in Figure 3B. The amount of transfer to the production of French and English words did not depend on the language that adaptation was acquired in, rANOVA interaction between training language and transfer language, $F(1, 19) = 3.16$, $p = .09$. In all four cases, transfer to the production of English and French words was significantly greater than zero, directional one-sample t tests—train French transfer French, $t(19) = 4.76$, $p < .001$, Cohen's $d = 2.18$; train French transfer English, $t(19) = 4.98$, $p < .001$, Cohen's $d = 2.28$; train English transfer French, $t(19) = 4.0$, $p < .001$, Cohen's $d = 1.84$; train English transfer English, $t(19) = 5.15$, $p < .001$, Cohen's $d = 2.36$.

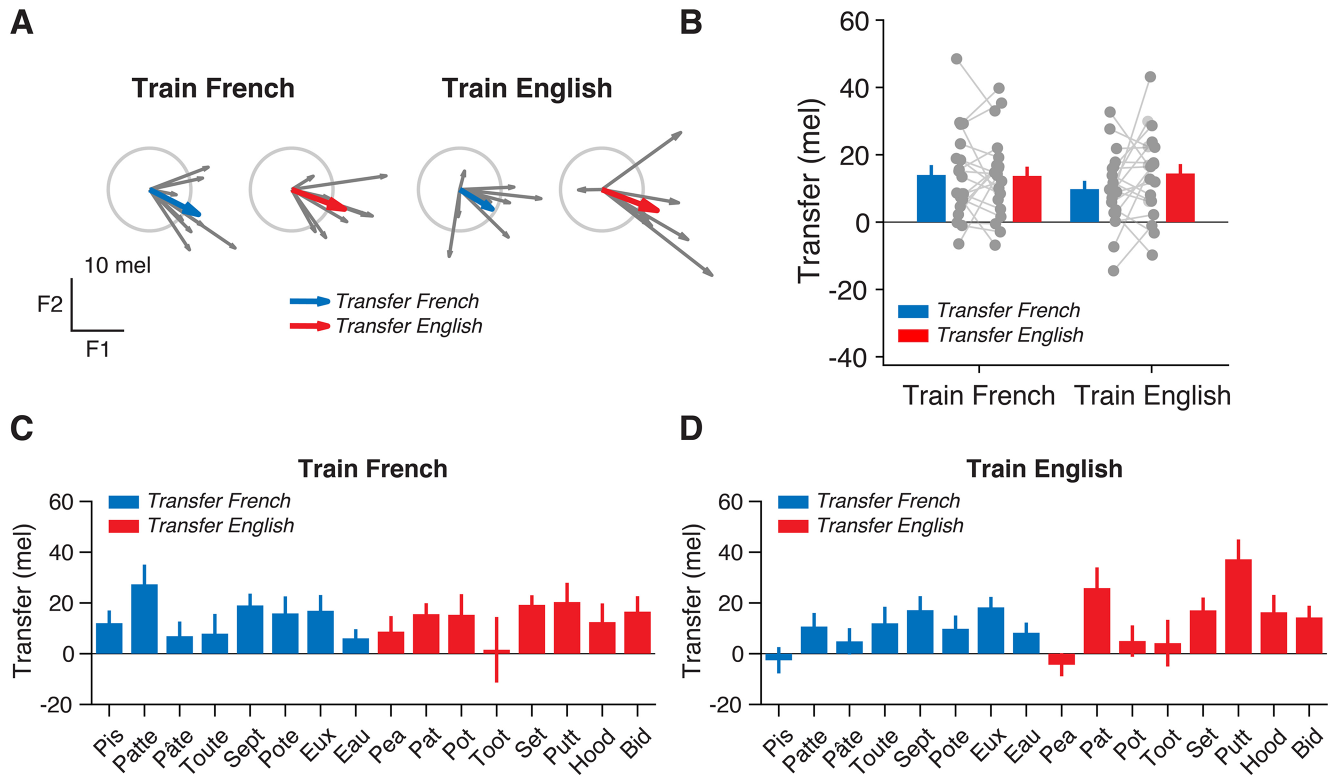
Figure 3C and D shows the amount of transfer to each of the French (blue) and English (red) words produced in the transfer task. The amount of transfer to specific words in French and English did not depend on the language participants trained in, rANOVA interaction between training language and transfer words, $F(15, 5) = 2.58$, $p = .15$. Furthermore, no significant differences in transfer were identified between the transfer words, rANOVA main effect of transfer words, $F(15, 5) = 2.34$, $p = .18$. Thus, in this sample of proficient bilinguals, a novel articulatory map for speech acquired in the context of one language was readily applied to the production of words with varying vowel sounds in the speakers' other language.

Did adaptation to altered auditory feedback persist throughout noise-masked speech? To test this, we examined whether changes in formant production from baseline were still present throughout the final washout block of sentence production in which the feedback alteration was removed (S7−S2). The aftereffect of adaptation averaged 14.16 mels (59% of the adaptation observed when the feedback manipulation was on) following French sentence production and 10.17 mels (44% of adaptation) following English sentence production. The aftereffect was significantly greater than zero in the case of French sentence production, directional one-sample t test, $t(19) = 6.09$, $p < .001$, Cohen's $d = 1.36$, and English sentence production, directional one-sample t tests, $t(19) = 2.87$, $p < .01$, Cohen's $d = 0.64$. Thus, adaptation persisted throughout the noise-masked speech produced in the transfer task.

In Experiment 2, we replicated the procedure and methods of Experiment 1, but with a different sample of Canadian bilinguals. In this case, 20 L1-English, L2-French speakers were recruited and tested in Wolfville, Nova Scotia.

The vectors in Figure 4A show how F1 and F2 changed in response to altered auditory feedback during the production of sentences in French (left) and English (right). As in Experiment 1, learned changes in production countered the induced change in the sound of the voice. These changes are quantified in Figure 4B, which shows the amount of adaptation for altered auditory feedback in Experiment 2 during the production of sentences in both French (blue) and English (red). Adaptation averaged 29.35% (20.55 mels) during the production of French sentences, and 36.24% (25.37 mels) during the production of English sentences. In both cases, adaptation was significantly greater than zero, directional one-sample t tests—French, $t(19) = 5.81$, $p < .001$, Cohen's $d = 2.67$; English, $t(19) = 4.37$, $p < .001$, Cohen's $d = 2.00$. There was no difference in the amount of adaptation associated with the production of French (L1) or English (L2) sentences, paired-sample t test, $t(19) = 0.71$, $p = .49$, Cohen's $d = 0.33$.

Figure 3
Experiment 1, Transfer



Note. (A) The gray vectors show the average F1–F2 change for the eight French (left) and eight English (right) words produced in the transfer task after altered feedback during French (train French) and English (train English) sentence production. The blue and red vectors show the average F1–F2 change across the words. (B) The bars depict transfer of speech adaptation to the production of French (blue) and English (red) words following altered feedback associated with French (train French) and English (train English) sentence production. The gray dots depict individual data points; the gray lines link data for each participant. (C) The blue and red bars show the amount of transfer to each of the eight French (blue) and eight English (red) words in the transfer task that followed altered feedback associated with French (train French) or, in panel (D), English (train English) sentence production. All error bars are ± 1 *SE*. F1 = first formant frequency; F2 = second formant frequency. See the online article for the color version of this figure.

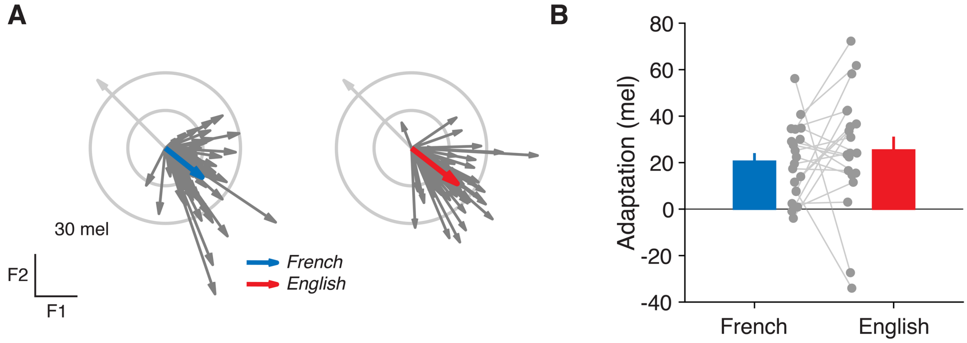
Thus, as in Experiment 1, speech adaptation was similar in the two languages, despite differences in proficiency between L1 and L2.

The vectors in Figure 5A show transfer of the adaptation acquired during French (*train French*) or English (*train English*) sentence production to the production of words in both French and English. The amount of transfer is quantified in Figure 5B. Transfer data for one participant were not included in the analysis as they were 2.5 *SD* away from the group mean for both French and English words (Figure 5B: shown in purple). As in Experiment 1, the amount of transfer to the production of French and English words did not depend on the language speech adaptation acquired in, rANOVA interaction between training language and transfer language, $F(1, 18) = 2.44$, $p = .14$. In all four cases, transfer to the production of English and French words was significantly greater than zero, directional one-sample t tests—train French transfer French, $t(18) = 2.17$, $p = .022$, Cohen's $d = 1.02$; train French transfer English, $t(18) = 2.28$, $p = .018$, Cohen's $d = 1.07$; train English transfer French, $t(19) = 4.93$, $p < .001$, Cohen's $d = 2.26$; train English transfer English, $t(19) = 5.0$, $p < .001$, Cohen's $d = 2.29$.

Figure 5C and D shows the amount of transfer to each of the French (blue) and English (red) words produced in the transfer task. The amount of transfer to specific words in French and English did not depend on the language participants trained in, rANOVA interaction between training language and transfer words, $F(15, 4) = 3.88$, $p = .10$. Although there was clear variability in the amount of transfer to each of the transfer words, no significant differences in transfer were identified between the transfer words, rANOVA main effect of transfer words, $F(15, 5) = 0.78$, $p = .68$. Thus, bilinguals in Experiment 2 were able to apply a novel articulatory plan for speech acquired in either an English or French context to the production of words with varying vowel sounds in both languages.

Finally, we examined if changes in formant production from baseline were still present in the final washout block of sentence production in which the feedback alteration was removed (S7−S2). The after-effect of adaptation averaged 6.39 mels (31% of adaptation) following French sentence production and 15.52 mels (61% of adaptation) following English sentence production. The aftereffect was significantly greater than zero in the case of French, directional one-sample t test, $t(19) = 2.04$, $p = .027$, Cohen's $d = 0.46$, and English sentence production, directional one-sample t tests, 2.64, $p < .01$, Cohen's $d = 0.59$. Thus, as in Experiment 1, adaptation persisted throughout the transfer task.

Figure 4
Experiment 2, Adaptation



Note. (A) The gray vectors show the average F1–F2 change for each of the 50 French (left) and English (right) sentences during altered auditory feedback. The blue and red vectors show the average F1–F2 change across sentences. (B) The bars depict F1–F2 change during French (blue) and English (red) sentence production in direct compensation for the formant alteration. The gray dots depict individual data points; the gray lines link data for each participant. All error bars are ± 1 *SE*. F1 = first formant frequency; F2 = second formant frequency. See the online article for the color version of this figure.

Discussion

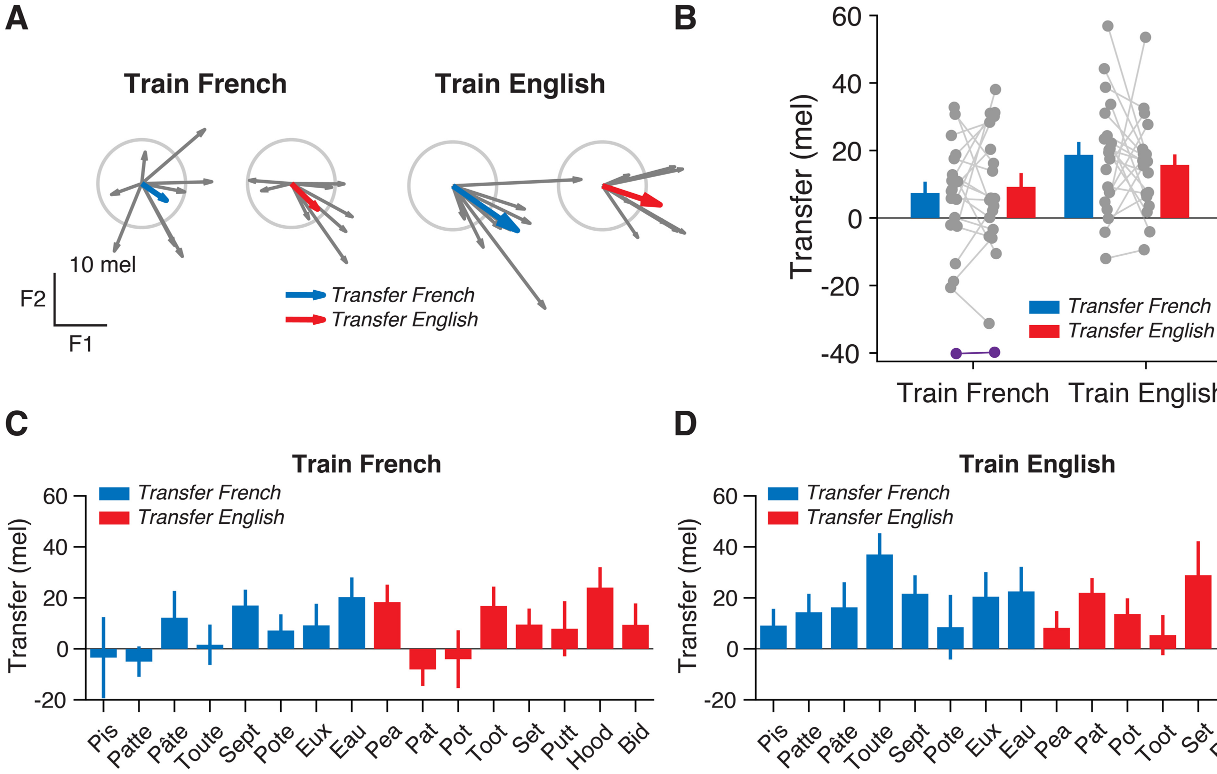
In addition to learning the grammar and vocabulary of two languages, bilinguals must also learn the relationship between speech sounds and articulatory motor plans in each language. Here, in two samples of bilingual speakers, we used real-time alterations of speech feedback to examine the extent to which articulatory plans for speech in one language influence those of a bilingual speaker's other language. Specifically, altered feedback was used to drive an adaptive change in the relationship between vowel sounds and articulatory plans for vowel production in either L1 or L2. We then tested the extent to which this adaptive change was applied to the production of vowels in the bilinguals' other languages. A comparable level of compensation to the feedback alteration was observed in both L1 and L2. Cross-language transfer of these novel articulatory plans for speech was observed to vowels in diverse regions of the vowel space. The amount of transfer was *not* influenced by proficiency—that is, transfer of articulatory adaptation from L1 to L2 was similar to transfer from L2 to L1. Thus, in proficient bilinguals, adaptive changes in speech production acquired in one language are immediately applied to the production of speech in their other language.

Prior work that examined the relationship between articulatory representations and language in bilinguals used indirect and observational measurements (e.g., acoustic measures of unaltered speech) to argue for asymmetries in cross-language interactions in relation to linguistic experience. In particular, Caramazza et al. (1973) concluded that there was little phonological interference from L2 to L1 during production, a result that has support from more recent work (Antoniou et al., 2011). Extending this finding to the current study, one might predict a gradient of transfer in relation to linguistic experience or simply less transfer from L2 to L1. This was not observed. In the bilinguals studied here, there was no effect of language on the cross-language transfer of adaptation to altered feedback, even from L2 to L1. This result does not support the idea that proficient bilinguals actively maintain separate articulatory representations in each language; rather it appears to support a cognitive architecture in which phonetic representations in French and English inhabit a shared vowel space. Under this model, the transfer of adaptation observed here is more akin to generalization across the vowel space. And generalization may have been broad because French and English comprise a number of phonetically similar vowels. Future work could test this idea using bilingual speakers of languages that share fewer vowels.

It is important to note that the proficiency of the bilinguals studied here differed from past studies that examined the relationship between articulation and language. For instance, a study by Alario et al. (2010), which argued for separate articulatory representations across languages in bilingual speakers, examined Spanish–French bilinguals who, in one group, had learned their L2 before the age of five and were immersed in an L2 environment. Here, we tested French–English and English–French bilinguals who reported moderate to high proficiency in their L2, but they were not all immersed in their L2 at the time of testing. Both groups were drawn from environments in which their L1 was their primary language. Such differences in the linguistic history of participants may account for discrepancies between the results of the current study and past work. Even so, here we present a novel method for using altered feedback to directly examine articulatory representations in bilinguals. Future work could apply this method to larger samples of bilinguals with more diverse linguistic backgrounds.

The results of the current study support the SLM—a psycholinguistic theory developed to integrate findings in adult L2 learners (Flege, 1995; Flege et al., 1999). The SLM is one of the only models to characterize both the perception and production of speech in late bilingual speakers (Chang, 2019). A feature of the SLM that distinguishes it from other theoretical frameworks of L2 learning is that interactions between L2 and L1 phoneme categories are predicted to be bidirectional (Chang, 2019). Our results expand on this framework by demonstrating that changes at the level of articulatory motor plans associated with phonemes produced in a speaker's L1 and L2 may interact. Specifically, the results show that changes to articulatory motor plans associated with L1 phonemes transfer to the production of L2 phonemes, and vice versa. The observation of transfer of articulatory adaptation from L1 to L2 and L2 to L1

Figure 5
Experiment 2, Transfer



Note. (A) The gray vectors show the average F1–F2 change for the eight French (left) and eight English (right) words in the transfer task that followed altered feedback with French (train French) and English (train English) sentence production. The blue and red vectors show the average F1–F2 change across words. (B) The bars depict transfer of speech adaptation to the production of French (blue) and English (red) words following altered feedback with French (train French) and English (train English) sentence production. The gray dots depict individual data points; the gray lines link data for each participant. The purple dots highlight an outlier that was removed. (C) The blue and red bars show the amount of transfer to each of the eight French (blue) and eight English (red) words in the transfer task that followed altered feedback with French (train French) or, in panel (D), English (train English) sentence production. All error bars are ± 1 *SE*. F1 = first formant frequency; F2 = second formant frequency. See the online article for the color version of this figure.

lends direct support to the SLM prediction that L1 and L2 interactions are bidirectional.

To date, only two studies have used altered auditory feedback to investigate the relationship between articulatory motor plans and language. Mitsuya et al. (2011) compared compensation to altered auditory feedback (involving an increase or decrease in F1 frequency) between L1-English speakers producing a single vowel in English, L1 Japanese speakers (who spoke English as a L2) producing a similar vowel in Japanese, and a different group of L1 Japanese (L2-English) speakers producing the same English vowel as produced by the L1-English group. Despite producing the same vowel sound and experiencing the same feedback alterations, the amount of compensation for altered feedback in one condition (an increase in F1 frequency) was found to differ between the English and Japanese speakers. The result suggests that cross-language differences in the processing of auditory feedback (related to the vowel space near the perturbed vowel) may, under certain conditions, influence speech–motor adaptation. This finding was conceptually replicated in work with L1-English and L1-French speakers (Mitsuya et al., 2013). Taken together, the studies suggest that differences in the organization of neighboring phonemes in the vowel space of each language influence the processing of feedback alterations and subsequent speech compensation.

In contrast to the between-language difference in speech adaptation observed in Mitsuya et al. (2013), the present study revealed no difference in the amount of compensation for altered auditory feedback between speakers producing sentences in English or French. One possible reason for this might be the specificity of the task used in Mitsuya et al. (2013); participants experienced a vowel alteration involving a pure F2 decrease during productions of a single vowel. The direction of the alteration was selected for its predicted differential effect in English and French. The specific combination of the formant alteration and vowel resulted in a perceptual "conflict" with neighboring (nonaltered) vowel categories that was presumed to give rise to differences in speech adaptation. In contrast, here the formant alteration involved an *increase* in F2 combined with a decrease in F1 applied to all vowels during sentence production. As all vowels were simultaneously altered, no such perceptual tension between neighboring vowel categories would be expected to arise.

Finally, there are constraints on the generality of the result. The study tested L1-French, L2-English and L1-English, L2-French bilinguals from two Canadian provinces. The extent to which the results of the study generalize to multilingual speakers of other languages, or to French–English bilinguals from other countries, is unclear. In addition, although the study had participants produce complete, grammatically complex sentences, the sentences were read from a computer screen. There are noted differences between read speech and conversational speech (Blaauw, 1994). The extent to which sensorimotor adaptation and the cross-language transfer of adaptation in bilinguals occurs during spontaneous speech (i.e., talking to a friend) remains unclear.

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(*Appendix follows*)

Appendix

Table A1
English Harvard Sentences

The birch canoe slid on the smooth planks.	*The heart beat strongly and with firm strokes.*
These days a chicken leg is a rare dish.	*Cut the pie into large parts.*
Rice is often served in round bowls.	*He lay prone and hardly moved a limb.*
Four hours of steady work faced us.	*The play seems dull and quite stupid.*
The source of the huge river is the clear spring.	*Move the vat over the hot fire.*
Help the woman get back to her feet.	*Leaves turn brown and yellow in the fall.*
A pot of tea helps to pass the evening.	*Weave the carpet on the right hand side.*
Smoky fires lack flame and heat.	*Type out three lists of orders.*
The soft cushion broke the man's fall.	*It caught its hind paw in a rusty trap.*
The girl at the booth sold fifty bonds.	*The wharf could be seen at the farther shore.*
Press the pants and sew a button on the vest.	*A cramp is no small danger on a swim.*
The swan dive was far short of perfect.	*He said the same phrase thirty times.*
Her purse was full of useless trash.	*Two plus seven is less than ten.*
Note closely the size of the gas tank.	*Bring your problems to the wise chief.*
What joy there is in living.	*The empty flask stood on the tin tray.*
The ship was torn apart on the sharp reef.	*The pencils have all been used.*
The wide road shimmered in the hot sun.	*The sofa cushion is red and of light weight.*
The rope will bind the seven books at once.	*At that high level the air is pure.*
A cup of sugar makes sweet fudge.	*There was a sound of dry leaves outside.*
A small creek cut across the field.	*The brown house was on fire to the attic.*
This is a grand season for hikes on the road.	*He wrote his last novel there at the inn.*
The dune rose from the edge of the water.	*Even the worst will beat his low score.*
A yacht slid around the point into the bay.	*The wreck occurred by the bank on Main Street.*
The two met while playing on the sand.	*The lamp shone with a steady green flame.*
The ink stain dried on the finished page.	*This will lead the world to more sound and fury.*

Table A2
French Harvard Sentences

Le canoë glissait sur les planches lisses.	*Le cœur battait par coups fermes.*
De nos jours, le poulet est un plat rare.	*Coupez la tarte en gros morceaux.*
Le riz est servi dans des bols.	*Il était sur le ventre et ne bougeait pas.*
Quatre heures de travail nous attendaient.	*La pièce semble ennuyeuse et stupide.*
L'origine de la rivière est la source.	*Mettez la cuve sur le feu.*
Aidez la femme à se remettre sur pied.	*Les feuilles deviennent jaunes à l'automne.*
Un pot de thé aide à passer la soirée.	*Tissez le tapis sur le côté droit.*
Les feux enfumés manquent de flamme.	*Tapez trois listes de commandes.*
Le coussin a amorti la chute.	*Il a attrapé sa patte dans un piège.*
La fille a vendu cinquante billets.	*On pouvait voir le quai sur la rive.*
Pressez le pantalon et cousez un bouton.	*Une crampe est un danger en natation.*
Le saut de l'ange était parfait.	*Il a dit la même phrase trente fois.*
Son sac à main était plein d'ordures.	*Deux plus sept font moins de dix.*
Notez bien la taille du réservoir d'essence.	*Rapportez vos problèmes au chef.*
Quelle joie il y a à vivre.	*La fiole se trouvait sur le plateau.*
Le bateau a été mis en pièces.	*Les crayons sont tous usés.*
La route scintillait sous le soleil.	*Le coussin du canapé est rouge et léger.*
La corde reliera sept livres à la fois.	*À cette altitude, l'air est pur.*
Une tasse de sucre fait du caramel.	*Il y avait un bruit de feuilles dehors.*
Un petit ruisseau traverse le champ.	*La maison était en feu jusqu'au grenier.*
C'est une belle saison pour les randonnées.	*Il a écrit son roman à l'auberge.*
La dune s'éleva au bord de l'eau.	*Même le pire battra son mauvais score.*
Un yacht a glissé autour de la pointe.	*L'accident s'est produit près de la banque.*
Les deux se sont rencontrés en jouant.	*La lampe brillait d'une flamme verte.*
La tache d'encre a séché sur la page.	*Cela conduira le monde à davantage de fureur*

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