Language experience and consonantal context effects on perceptual assimilation of French vowels by American-English learners of French[a)]

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Recent research has called for an examination of perceptual assimilation patterns in second-language speech learning. This study examined the effects of language learning and consonantal context on perceptual assimilation of Parisian French (PF) front rounded vowels /y/ and /œ/ by American English (AE) learners of French. AE listeners differing in their French language experience (no experience, formal instruction, formal-plus-immersion experience) performed an assimilation task involving PF /y, œ, u, o, i, ɛ, a/ in bilabial /rabVp/ and alveolar /radVt/ contexts, presented in phrases. PF front rounded vowels were assimilated overwhelmingly to back AE vowels. For PF /œ/, assimilation patterns differed as a function of language experience and consonantal context. However, PF /y/ revealed no experience effect in alveolar context. In bilabial context, listeners with extensive experience assimilated PF /y/ to /ʲu/ less often than listeners with no or only formal experience, a pattern predicting the poorest /u-y/ discrimination for the most experienced group. An "internal consistency" analysis indicated that responses were most consistent with extensive language experience and in bilabial context. Acoustical analysis revealed that acoustical similarities among PF vowels alone cannot explain context-specific assimilation patterns. Instead it is suggested that native-language allophonic variation influences context-specific perceptual patterns in second-language learning. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3050256]

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I. INTRODUCTION

The present study investigated the effects of second-language (L2) experience and consonantal context on the perceptual assimilation of Parisian French (PF) front rounded vowels by American English (AE) L2-learners of French. The class of vowels investigated in this study exemplifies the difficulty individuals may encounter upon learning L2 segments. Front rounded vowels, such as PF /y/ (vu /vy/ "seen") and /œ/ (in vœu /vœ/[1] "wish"), are produced with rounded lips, but unlike AE rounded vowels, the tongue body is described as being forward in the oral cavity (Tranel, 1987). The second and third formant frequencies (F2 and F3) of front rounded vowels are lower than those of front unrounded vowels, primarily because the length of the oral cavity is increased through lip rounding. Front rounded vowels are arguably nonexistent in AE and certainly not phonemic in the language (Gottfried, 1984). Findings conflict regarding whether AE listeners perceive (and produce) front rounded vowels in a nativelike manner (e.g., Best *et al.*, 1996; Flege, 1987; Flege and Hillenbrand, 1984; Gottfried, 1984; Levy and Strange, 2008; Polka, 1995; Rochet, 1995; Stevens *et al.*, 1969; Strange *et al.*, 2005), as will be discussed below.

A. Models of non-native and second-language speech perception

Two predominant models of cross-language speech perception, the Perceptual Assimilation Model for naïve listeners (PAM) and L2-learners (PAM-L2) (Best, 1995; Best and Tyler, 2007) and the Speech Learning Model (SLM) (Flege, 1995), posit that the perceived similarity of non-native segments to native categories is crucial to determining the difficulties listeners will encounter in their non-native language. In proposing the PAM-L2, Best and Tyler (2007) explored whether the principles involved in naïve learners' patterns of perceptual assimilation may be extended to perceptual patterns in L2-learning. Unlike the SLM, which focuses more on the L2 perception-production link, the PAM makes testable predictions in the realm of perception, specifically the relationship between assimilation and discrimination of non-native sounds (Harnsberger, 2001). Because the present study drew on findings from identification and discrimination studies to create testable predictions regarding assimilation in L2-learners, the PAM-L2 framework is discussed in greater depth here than the SLM.

The PAM (Best, 1995) posits that novel segments may be perceptually assimilated to native categories as "good" to "poor" instances along a continuum. In single-category assimilation, for example, contrastive non-native segments are both assimilated as good instances of the same category in the native language. In the category-goodness type, two non-native segments are assimilated into the same native cat-

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egory, but one is a "better instance" than the other. If each non-native segment is assimilated to a different native category, this constitutes two-category assimilation. On the other hand, a segment may be "uncategorizable," that is, within the phonological space of the native language but outside any actual native category, whereas another may be similar to an AE category (uncategorized-categorized). And finally, both segments may be uncategorizable within the native-language inventory.

Perceptual assimilation patterns predict naïve listeners' ability to differentiate foreign speech sounds according to the PAM (Best, 1995). In presenting the PAM-L2, Best and Tyler (2007) demonstrated how predictions in the PAM framework may also predict success in L2 perceptual learning. According to the PAM, two non-native segments assimilating to a single native category are expected to be the most difficult contrasts to discriminate, especially if they are equally good instances of the category. Segments assimilating to separate native categories or as better and worse exemplars or as uncategorizable and categorizable exemplars will yield more accurate discrimination than would single-category assimilation. The PAM-L2 posits that in category-goodness assimilation, it is unlikely that a new category would be learned for the less deviant L2 phone. If both L2 phones are uncategorizable, learning patterns would depend, in part, on whether the L2 phones are perceived as similar to L1 phones that approximate each other in phonological space. Experiments inspired by the PAM have focused mostly on naïve listeners (e.g., Best *et al.*, 1988, 1996; Strange *et al.*, 2001). Few studies (e.g., Guion *et al.*, 2000, on consonant perception) have examined L2-learners' assimilation patterns.

Unlike the PAM (Best, 1995) for naïve listeners, Flege's (1995) SLM was designed specifically to explain the difficulties more experienced language learners face when learning L2 contrasts, with emphasis on the problem of inaccurate production (i.e., accentedness) by L2-learners and changes in production with exposure to L2. The PAM and the SLM concur that when non-native speech sounds are identified with one particular native category, discrimination difficulties ensue. However, the SLM specifies that it is at an allophonic level that L1 and L2 sounds relate, although the consequences for cross-language speech perception are not defined (Harnsberger, 2001). According to the SLM, the more perceptually dissimilar an L2 segment is from its closest L1 segment, the greater the likelihood that their phonetic differences will be discerned. New L2 categories may be established if at least some of the phonetic differences between L1 and the L2 speech sounds are discerned.

B. Previous perceptual research on French front rounded vowels

Several studies have demonstrated the effects of language background on perception of French rounded vowels. Rochet (1995) asked Canadian French, native Canadian English, and Brazilian Portuguese listeners to identify steady-state synthetic vowels on a high vowel continuum in which the second-formant (F2) frequency varied between 2500 and 500 Hz, as /i/ or /u/ (or /i-y-u/ for Canadian French listeners). Stimuli identified as /y/ by Canadian French listeners were most frequently identified (and produced) as /u/ by Canadian English listeners and as /i/ by Brazilian Portuguese listeners. Clearly, the participants' language background influenced to which native-language categories (/i/ or /u/) the segment (/y/) assimilated.

Using a perceptual assimilation task, Best *et al.* (1996) found that 8 of 13 naïve AE listeners assimilated Bretagne French front rounded vowels in /sœ-sy/ in a two-category pattern, 3 in an uncategorizable-categorizable pattern, and 2 in a category-goodness pattern. In a categorial AXB discrimination task, the listeners discriminated multiple tokens of the French syllables with fewer than 5% errors, consistent with the PAM's predictions of very good to excellent discrimination for 11 of the 13 listeners' assimilation patterns revealed. Consistent with Best *et al.*'s (1996) finding of little difficulty for naïve AE listeners on contrasts involving /y/, Flege and Hillenbrand (1984) reported high accuracy (90% correct) in identifying native French /ty/ by experienced AE listeners in a paired-comparison (/tu/ and /ty/) task, suggesting that the French /y-u/ contrast can be differentiated accurately by AE speakers, at least when presented in paired syllables. Flege and Hillenbrand (1984) referred to the French front rounded vowel /y/ as an example of a "new" L2 phone to American learners of French, as listeners are able to distinguish it from French /u/ in perception and production. However, Flege (1987) stated that in certain phonetic contexts, AE /u/ has an /y/-like phonetic quality, a topic he suggested ought to be explored. According to Flege (1987), AE learners of French may initially classify /y/ as /u/, but with experience, they will recognize that /y/ is not a realization of English /u/.

C. Context-dependent perception

Vowels are produced differently as a function of consonants surrounding them (Hillenbrand *et al.*, 2001) and coarticulatory variation differs from language to language (Strange *et al.*, 2007). It follows that cross-language perceptual patterns may also vary as a function of phonetic context (Bohn and Steinlen, 2003). Consonantal context (i.e., bilabial, alveolar, or velar) affects naïve Japanese listeners' assimilation of non-native vowels (Strange *et al.*, 2001). Moreover, naïve AE listeners' assimilation of North German front rounded vowels varies as a function of prosodic and consonantal context (Strange *et al.*, 2004a, 2007).

If learning an L2 involves learning to produce and perceive coarticulatory variation in the language, the ability to perceive L2 segments may also change with L2 experience and vary as a function of phonetic context. A seminal study by Gottfried (1984) examined the effect of syllabic context on perception of French vowels by AE listeners with and without L2 experience. AE listeners who spoke French discriminated vowels in /tVt/ context more accurately than those who spoke no French; the groups did not perform differently for vowels in isolation. Vowel perception may thus vary as a function of experience and syllabic context.

Levy and Strange (2008) extended Gottfried's (1984) study, focusing on the consonantal context effects on the perception of PF /y/, /œ/, /u/, and /i/. In this (cross-speaker[2])

categorial discrimination experiment, PF vowels were presented in /rabVp/ and /radVt/ bisyllables embedded in AXB triads of the phrase "neuf /raCVC/ à des amis" ("nine /raCVC/ to some friends"). Experience and context affected AE listeners' perceptual accuracy. Experienced listeners made fewer errors than the inexperienced group for three vowel pairs (/i-y/, /u-œ/, and /y-œ/). For /u-y/, no significant difference was found between the naïve group (24% errors) and the experienced group (30% errors) in their discrimination, despite the experienced group's many years of French instruction and immersion. The inexperienced group made more errors on the /u-y/ contrast in alveolar context than in bilabial context, but more errors on the /i-y/ contrast in bilabial context than in alveolar. The experienced group, on the other hand, did not reveal a significant context effect on discrimination of the /u-y/ contrast. For all contrasts except /i-y/ (where the reverse was true), for the inexperienced group, discrimination scores were higher in bilabial than in alveolar context. No significant context effect was revealed for the experienced group, although they showed a trend toward more errors in alveolar context. Thus, with language experience, L2-learners may begin to perceive segments on a more abstract level, less affected by acoustic variation.

Discrimination results from Levy and Strange (2008) suggested that L2 vowels may be perceptually assimilated to native vowel categories in a consonantal-context-dependent manner that changes with language experience. The present study explored the effects of consonantal context on *perceptual assimilation* patterns as listeners have more extensive L2 experience, thereby examining the extension of the PAM's (Best, 1995) theoretical domain to L2-learning. Perceptual assimilation of PF front rounded vowels by three groups of AE listeners was investigated: listeners with no French experience (NoExp), listeners with formal (i.e., classroom) French training (ModExp), and listeners with several years of formal French training and immersion experience (HiExp). The ModExp group was included to represent L2 vowel perception by the majority of students enrolled in United States schools, who begin studying a foreign language at an average age of 12 (Pufahl *et al.*, 2001) and who do not have immersion experience. Phrases were used rather than vowels or words in isolation in order to tap into linguistic categorization processes employed in the perception of continuous speech.

The following questions were asked, and predictions were made:

(1) Are PF front rounded vowels perceptually assimilated to AE front, unrounded or back, rounded vowels by L2-learners of French? Based on the PAM-L2's (Best and Tyler, 2007) claim that discrimination is typically poor when two L2 phones assimilate to a single L1 category, the expectation here was that, overall, the L2-learners would assimilate PF front rounded vowels to AE back rounded vowels more often than to AE front unrounded vowels.
(2) Does perceptual assimilation of PF front rounded vowels by L2-learners vary as a function of language experience? It was predicted that assimilation patterns for PF /œ/ would generally differ with language experience for these L2-learners but that the PF /y/ would be perceived similarly across groups. Goodness ratings were expected to decrease with experience based on the PAM-L2's (Best and Tyler, 2007) claim that L2-learning involves, to the extent possible, refining the learner's perception of higher order invariants in the L2. As no previous study had compared assimilation of PF vowels by AE listeners with formal French experience versus formal training plus immersion experience, it remained to be seen whether the ModExp group would demonstrate assimilation patterns more like NoExp or HiExp listeners.
(3) Does perceptual assimilation of PF front rounded vowels by L2-learners vary as a function of consonantal context and (4) are there interactions among perceptual assimilation of particular vowels, language experience, and context? Based on the PAM-L2's (Best and Tyler, 2007) claim of an association between perceptual assimilation and discrimination patterns in L2-learners and on Levy and Strange's (2008) observation that only beginning L2-learners showed context-specific patterns in discrimination, more assimilation of PF front rounded vowels to back vowels in alveolar context (than in bilabial context) was predicted for naïve listeners, with less of a context effect expected with more extensive language experience.

II. METHOD

A. Participants

A total of 43 native AE speakers volunteered as listeners for the tests. Participants were recruited from Columbia University, the Alliance française, a French conversation club, and the web.[3] Participants passed a bilateral hearing screening at 20 dB at 500, 1000, 2000, and 4000 Hz. Data from four of these participants were discarded for the following reasons: One participant failed the hearing screening, and two exceeded the criteria for errors in the familiarization task. Another participant revealed a language history that did not meet the inclusion criteria for the "moderate experience" group (of no more than two years of French in high school and of minimal French immersion) or for the "high experience" group (of having spent more than one year in a French-speaking country). Thus, data from 39 AE participants (13 in each language group) were analyzed.

All participants were born and raised in English-speaking households in the United States. None had had more than a year of instruction in any language with front rounded vowels aside from French. Of the 39 AE listeners, 13 were native AE speakers living in New York City, ages 20–40 years, with minimal French experience (NoExp group), i.e., no French instruction and little interaction with French speakers.

The second group, listeners with moderate French experience (ModExp group), consisted of 13 native speakers of AE living in New York City, ages 22–37 years, who had had formal French training (i.e., they had attended French classes) but minimal immersion in French. They had begun learning French in school no earlier than age 12 years

(mean=16.1, SD=2.8) and had received a mean of 3 years of instruction in French (range=2–4 years, SD=0.8) in high school and college. Their instruction occurred from .5 to 6 years before testing (mean=3.3 years, SD=1.6). They had spent no more than 5 months in a French-speaking country and had not been speaking French around the time of testing.

The third group, AE listeners with extensive French experience (HiExp), consisted of 13 native speakers of AE, ages 20–61 years,[4] who had extensive formal training and immersion experience in French and were using French regularly at the time of testing (range=2 h/week, 100% of the time, median=15 h/week). They had had a mean of 8 years of French instruction (range=5–13 years, SD=2.4), which began no earlier than age 12 (mean age of beginning learning: 14 years, SD=1.6). They had spent at least a year in a French-speaking country as adults (range=1 year to 16 years, median=1.4 years), had spoken French regularly in their professions (e.g., as teachers of French, translators, and foreign business consultants), and were currently using French. Three were living in France at the time of testing and were visiting New York. One had lived in France until 3 weeks before testing.

B. Stimulus materials

1. Recording, editing, and verification procedures

Recordings of three female adult native PF speakers were made in an IAC chamber. These speakers had resided in the U.S. for less than a year. They were instructed to read a list consisting of nine PF vowels, blocked by /rabVp/ or /radVt/ context, in the sentence: "J'ai dit neuf /raCVC/ à des amis" (I said nine /raCVC/ to some friends). They read four repetitions of each list and were asked to produce the sentences as if conversing with a native speaker.

The experimenter (a native speaker of French and English) conversed in French with the speakers. A Shure microphone fed signals through an Earthworks microphone preamp to a Soundblaster Live Wave sound card of a Dell Dimension XPS B800 computer. The stimuli were digitized with a sample rate of 22,050 Hz, 16 bit resolution, on a mono channel, using SoundForge™ software. The experimenter chose the three "best" instances of each vowel. A native French speaker judged whether the tokens were typical exemplars of the target vowel. Two tokens were replaced because the intonation on these stimuli did not match the others. The digital files were edited so that only the phrases "neuf /rabVp/ à des amis" and "neuf /radVt/ à des amis" remained, with the target front rounded vowels /y, œ/ and the vowels /i, u, ɛ, o, a/ for comparison. For stimulus verification, three monolingual native speakers of PF who had been in the United States for less than a month identified each stimulus. They made 0 errors and rated the stimuli a median of 9 on a 1–9 scale from foreign sounding (1) to native French sounding (9), indicating that these were good tokens of the intended categories. In order to examine the acoustic differences that might affect vowel perception, an acoustical analysis of the French vowel stimuli was performed.

2. Acoustic analysis

Acoustic analysis was performed by means of customized software in MATLAB (CVCZ by Valeriy Shafiro). First, the onset and offset of the syllable containing the target vowel (i.e., /bVp/ or /dVt/) were determined on the basis of the following operational definitions: Onset was defined as a change in amplitude, indicating release of the preceding consonantal occlusion. Offset was defined as the decrease in periodic energy indicated in F2 and F3 on a spectrogram coinciding with decreased amplitude on the waveform, indicating the beginning of closure of the following consonant. The program then calculated the temporal midpoint between onset and offset of the syllable and derived the first three formant frequencies for a 25 ms window centered around that point using linear predictive coding analysis (24 coefficients).

The top scatter plot in Fig. 1 represents all vowel stimuli (i.e., three tokens per speaker) uttered by the three PF speakers in bilabial /rabVp/ context with the F2 frequency along the *X*-axis and the F1 along the *Y*-axis (in barks).[5] For purposes of comparison, these are superimposed onto average values for seven (long) AE vowels (in symbols connected by dashed lines) spoken in bilabial context in nonsense trisyllables in sentences by three female AE speakers (Strange *et al.*, 2007). The AE vowel space appears to be shifted down (higher F1 values) relative to PF vowels; however, the relative distance of PF and AE vowels on the front-back dimension (F2 values) can be compared meaningfully. In bilabial context, PF front rounded /y/ is nearest to AE and PF front unrounded /i/, actually overlapping with tokens of PF /i/ across speakers of the same gender. Crucially, in this context, PF /y/ is far closer to /i/ than to /u/ in both languages. PF /œ/ is intermediate between front and back AE vowels.

The bottom plot represents the PF vowel stimuli in alveolar /radVt/ context, superimposed on average values for AE vowels spoken in alveolar context (Strange *et al.*, 2007). It should be noted that the front unrounded vowels, especially /i/, in both languages are little affected by changes in consonantal context. Front rounded PF /y/ remains at the "front" of the vowel space, some tokens overlapping with PF /i/ across speakers. However, the vowel spaces for both languages are generally more constricted along the front-back dimension because both PF and AE back vowels /u/ and /o/ (and AE /ʊ/, not shown here) are "fronted" (produced with higher F2 frequencies) in alveolar context relative to bilabial context. However, all tokens of PF /y/ remain closer to PF /i/ than to PF /u/ in alveolar context, whereas they are spectrally intermediate between AE /u/ and /i/. PF /œ/ is only slightly fronted. PF /o/ approximates both AE and PF /u/ more in bilabial than in alveolar context.[6] PF /a/ tokens are generally produced with higher F2 values in alveolar context than in bilabial context.

The acoustic analysis of the stimuli demonstrates that in bilabial context, PF /y/ was far closer to /i/ than to /u/ in both languages; thus, if the naïve participants and L2-learners perceptually assimilated /y/ to AE back vowels in bilabial context, acoustics alone would not explain their assimilation patterns. Furthermore, the relationship of the PF stimuli to AE vowels described above suggests that if the participants per-

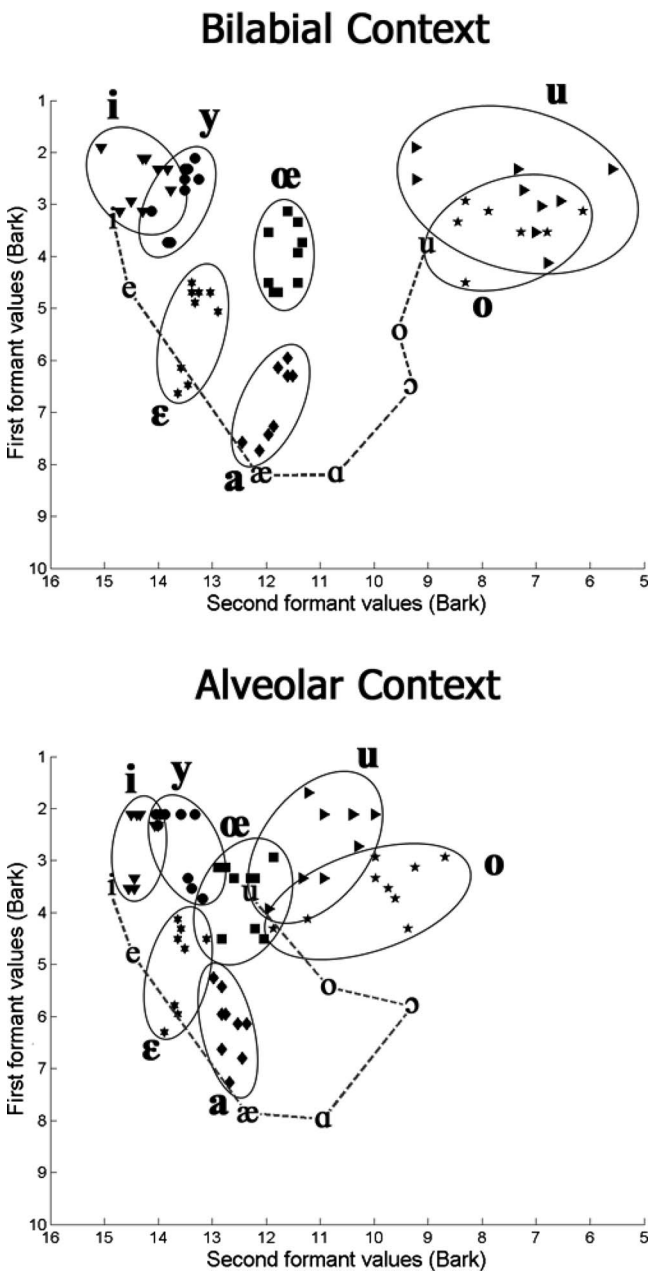

FIG. 1. Formant 1/formant 2 vowel spaces for bilabial /rab Vp/ stimuli (top) and alveolar /rad Vt/ stimuli (bottom) uttered in carrier phrases by three native speakers of PF. For comparison purposes, averages (in symbols connected by dashed lines) of four tokens from three monolingual female speakers of AE in bilabial /gəbVpə/ context (top) and alveolar /gədVtə/ context (bottom) in phrases from the production study of Strange *et al.* (2007) are provided.

ceptually assimilated front rounded vowels to back vowels more often in alveolar context, this may be more a function of the fronting of AE back vowels, i.e., of their native vowel space, than of the PF vowel space.

C. Procedure

The stimulus files were transferred via a zip disk to a Dell Dimension XPS B800 computer. Participants listened to stimuli presented via STAX Professional SR Lamda headphones connected to a STAX Professional SRM-1/MK-2 amplifier, receiving the signal from the computer. Sessions took place in the sound-attenuated chamber. Stimuli were entered into a customized software program designed to execute the perceptual assimilation task.

Prior to the experimental trials, keyword, task, and stimulus familiarization procedures trained listeners to choose appropriate responses and become familiar with the stimuli. In the keyword familiarization task, the experimenter asked the participant to read the 13 (AE) keywords ("heed, hid, hayed, head, had, hod, hawed, hud, hoed, hood, who'd, hued, herd") aloud to her. In the present experiment, the word "hued" was included as an AE keyword response option based on the finding that AE learners of French frequently produce /ʲu/ in French conversation when targeting the production of /y/ (Levy and Law II, 2008).

Task familiarization began with the presentation of AE phrases "five /gəCVCə/ this time" with the AE vowels (/i/, /ɪ/, /e/, /ɛ/, /æ/, /ɑ/, /ɔ/, /ʌ/, /o/, /ʊ/, /u/, /ʲu/, /ɝ/) in randomly presented /bVp/ and /dVt/ contexts recorded by a female native AE speaker, with keyword response alternatives and feedback. The listener was instructed to select the AE keyword that contained the vowel most similar to the second vowel of the nonsense word and then to rate the vowel from 1–9 according to how nativelike (9) or foreign sounding (1) the vowel was. On the last block (block 4), no feedback was provided, and listeners needed to achieve a criterion of no more than one error in identifying a particular AE vowel token and no more than three errors altogether in order to proceed to the stimulus familiarization.

The overall structure of the remaining blocks was the following: Stimuli were blocked by context. Thus, half of the listeners were presented all of the French stimuli in bilabial context before hearing the stimuli in alveolar context, and the other half were presented stimuli in alveolar context before bilabial. Stimulus familiarization consisted of a block of one token each of the seven PF vowels in the stimulus phrases and did not include feedback.

The perceptual assimilation experiment began with instructions presented to participants on the computer screen. Participants were instructed to listen to each phrase, paying attention to the second vowel (e.g., /radVt/) in the target nonsense word of each phrase. They were asked to focus on the target vowel and to try to ignore other aspects of the phrases (e.g., consonants or intonation) that might be distracting or sound different from English. The stimulus was presented once. The listeners saw the 13 AE keywords and chose the one that contained the vowel that was most similar to the target vowel. They heard the stimulus again and rated the French vowel on a scale of 1–9. A rating of 1 indicated "most foreign sounding," 9 indicated "most English sounding," and participants were encouraged to rate the stimulus as any number in between using the whole spectrum of the scale.

The test blocks contained all three tokens of each of seven French vowels by each speaker. Blocks were presented twice, with stimuli randomized within blocks. The presentation order of speakers within each context was determined by a Latin square. Each vowel was presented twice in each con-

sonantal context, in phrases. Each participant completed six judgments for each speaker's three vowel tokens, totaling 18 judgments per vowel per context.

III. RESULTS

A. Data analysis

The frequencies of selecting a particular response category in the perceptual assimilation task were tallied for each French vowel across all listeners within each language group within each consonantal context (summing over 18 judgment opportunities for each listener in each context). Frequencies of the modal response and the other chosen responses for each PF vowel stimulus were converted to percentages of total trials. The median goodness ratings for each AE response category were then computed. Because the range of median ratings was not large (mdn=3–7 for most vowels), the focus of the analysis is on response percentages as that appears to provide more telling information regarding perceived similarity.

To assess the effects of language experience and consonantal context on the perceptual assimilation patterns, a multinomial baseline-category logistic regression model (Agresti, 2007) was fit to the data. The most often chosen response category for the HiExp group was used (arbitrarily) as the baseline category. Standard errors and confidence intervals for the estimated odds ratios (ORs) were analyzed to judge whether the outcome was statistically significant, which meant here that the ORs were judged to be significantly different from 1.

In order to sort out inter- and intraparticipant variability, an "internal consistency" analysis of perceptual assimilation results was performed. Internal consistency was determined by examining each listener's modal responses, i.e., for each PF vowel, what percentage of trials each listener assimilated the vowel to his or her AE modal category, regardless of what that category was. The mean consistency score for each group was calculated. Internal consistency scores across all PF vowels and for each front rounded vowel are reported. A high internal consistency score indicates that individual listeners consistently gave the same response to a particular stimulus, whereas a low score suggests that they gave several different responses.

B. Overview of results

Table I displays the modal AE categories chosen by the NoExp group, the ModExp group, and the HiExp group for all PF stimuli presented in bilabial context (above) and in alveolar context (below). Within each language group, the left-hand column lists the PF stimuli. The second column represents the AE responses chosen. The "mode percent chosen" indicates the percentage of trials that the most frequent AE responses were chosen by the group. The median rating indicates the median of goodness ratings from 1 (most foreign sounding) to 9 (most AE sounding) for the trials in which each AE response category was selected. Only AE vowel responses chosen on at least 10% of trials (i.e., 23 responses out of 234 possible) in at least one consonantal context by at least one group are listed and analyzed.

The multinomial linguistic regression analysis revealed language experience effects for some comparisons on all PF vowels except /i, u/, for which the vast majority of responses were the AE /i/ and /u/, respectively. Significant consonantal context effects were found for /a, y, o, æ/, but not for /i, ɛ, u/. For some PF vowel categories, language experience effects were significant. Thus, the comparisons for each vowel were analyzed individually. (The Appendix lists the comparisons performed using the regression analysis and their resulting statistical significance or nonsignificance.) These results are discussed in detail below.

Overall, median goodness ratings were lower in the NoExp group than in the HiExp group for modal responses to /i/, /y/, /u/, /ɛ/, and /a/ but not to /œ/. The front rounded vowel /y/ received the lowest goodness ratings (median =6,3,3 by NoExp, ModExp, and HiExp, respectively, in bilabial context; median=4,3,2 by NoExp, ModExp, and HiExp, respectively, in alveolar context).

A three-factor (language experience × vowel × context) analysis of variance was performed to examine the internal consistency of perceptual assimilation of all vowels. The dependent variable in this analysis was internal consistency (calculation described above), and the independent variables were level of language experience, consonantal context, and vowel. A significant language experience effect was revealed [$F(2,545)=33.28$, $p<0.0001$], suggesting that with language experience, individual listeners selected their modal response more often. Controlling for consonantal context and vowel, individuals with moderate language experience were not significantly more consistent in their responses than those with no language experience [$F(1,545)=0.62$, $p=0.4314$], but the HiExp group responded more consistently than the ModExp group [$F(1,545)=44.08$, $p<0.0001$] and the NoExp group [$F(1,545)=55.15$, $p<0.0001$]. Consonantal context was revealed as a significant factor [$F(1,545)=9.82$, $p=0.0018$] in response consistency, with more consistency found in bilabial (mean=86.829, SD=17.08) than in alveolar context (mean=82.89, SD=18.45) context. A significant vowel effect was found [$(F(6,545)=23.31$, $p<0.0001$], suggesting that some vowels were assimilated in a more consistent manner than others. For example, responses to /y/ (mean=86.69, SD=13.41) were less consistent than to /i/ (mean=98.23, SD=3.56) but more consistent than to /œ/ (mean=76.46, SD=19.02).

In the following sections, the AE naïve listeners and L2-learners' perceptual assimilation patterns for PF front unrounded and low vowels (PF /i, ɛ, a/) will be presented to provide a basis for comparison with the PF other vowels, followed by their perceptual assimilation of PF back rounded vowels (/o, u/) and of front rounded vowels (/y, œ/).

C. Perceptual assimilation of front unrounded and low PF vowels /i/, /ɛ/, and /ɑ/

PF /i/ was perceptually assimilated to AE /i/ on 99% of responses and received the highest goodness ratings (7–8) of all vowels, suggesting that this was an excellent fit to the AE /i/ category for naïve and experienced listeners alike and that listeners were on task.

TABLE I. Perceptual assimilation of PF vowels /i, ɛ, a, o, u, y, œ/ in bilabial /rabVp/ and alveolar /radVt/ contexts by AE listeners with no French experience (No Exp), moderate French experience (Mod Exp), and extensive formal+immersion French experience (Hi Exp): Percent chosen for each response and median goodness ratings (in parentheses) are presented for each vowel. For each AE vowel stimulus, only responses chosen on at least 10% of the trials (i.e., 23 responses out of 234 possible) in at least one consonantal context by at least one experience group are listed. [Total number of responses per vowel =234 (i.e., 18 judgments per vowel per context by 13 participants in each group).]

	No Exp			Mod Exp			Hi Exp		
PF	AE	%	Med	AE	%	Med	AE	%	Med
				Bilabial context					
i	i	98	8	i	99	7	i	100	7
ɛ	ɛ	79	7	ɛ	85	6	ɛ	89	6
	æ	12	6	e	11	5	e	10	6
a	ɑ	58	6	ɑ	52	5	ɑ	56	4
	æ	36	6	æ	34	6	æ	43	6
o	u	62	7	o	71	6	o	99	6
	o	24	7	u	18	4	u	1	4
u	u	90	7	u	85	4	u	78	6
	ʲu	6	4				o	13	4
y	ʲu	80	6	ʲu	85	3	ʲu	72	3
	i	12	4	u	13	3	u	28	3
œ	ʊ	38	6	ʊ	65	4	ʊ	60	6
	u	34	6	ʌ	12	4	ɝ	27	5
	ɝ	1	7	u	11	3	ʌ	8	4
				Alveolar context					
i	i	97	7	i	98	7	i	99	7
ɛ	ɛ	76	6	ɛ	90	6	ɛ	95	6
	e	11	6	e	10	6	e	4	5
	æ	10	6						
a	æ	57	7	æ	48	6	æ	62	6
	ɑ	29	7	ɑ	30	5	ɑ	35	6
	ɛ	12	6	ɛ	18	6			
o	u	43	6	o	69	5	o	98	6
	o	41	6	u	19	4			
u	u	84	6	u	75	4	u	91	6
	ʲu	9	4	ʲu	15	3			
y	ʲu	65	4	ʲu	71	3	ʲu	61	2
	u	31	6	u	24	4	u	34	4
œ	u	59	6	ʊ	40	3	ʊ	61	5
	o	17	6	o	25	4	ɝ	20	6
	ʊ	17	5	u	23	4	u	9	4

Results for PF /ɛ/ indicate significant differences in perceptual assimilation patterns as a function of language experience [$\chi^2(6)=49.56$, $p=0.0001$] but not of consonantal context [$\chi^2(3)=0.47$, $p<0.3250$]. Listeners with extensive language experience perceptually assimilated PF /ɛ/ more often to AE /ɛ/ (as opposed to AE /e/ or AE /æ/). However, the language experience effect was not statistically significant for all comparisons. For example, no significant language experience differences were found in the estimated odds of perceptual assimilation of PF vowel /ɛ/ to AE /e/ versus that to the reference category AE /ɛ/ (NoExp versus ModExp OR=0.8704, $p=0.5466$; ModExp versus HiExp OR=0.657, $p=0.0757$; NoExp versus HiExp OR=1.32, $p=0.2606$). However, for the AE /æ/ responses versus /ɛ/ responses, the NoExp listeners differed significantly in their estimated odds of selecting /ɛ/ over /æ/ from the estimated odds of the ModExp listeners selecting /ɛ/ over /æ/ (OR =8.39, $p<0.0001$) and from the estimated odds of the HiExp selecting /ɛ/ over /æ/ (OR=30.7, $p<0.0001$). In contrast, no significant differences were found between the odds of a listener in the ModExp group and a listener in the HiExp group selecting /ɛ/ over /æ/ (OR=3.662, $p=0.1068$).

Results for the perceptual assimilation of vowel /a/ provide evidence of a significant language experience effect

$[\chi^2(4)=36.77,\ p<0.0001]$ and a consonantal context effect $[\chi^2(2)=82.65,\ p<0.0001]$. AE /æ/ was the overall modal choice in alveolar context (56%), and AE /ɑ/ was second-most chosen (31%), whereas /ɑ/ was the modal choice (55%) in bilabial context and /æ/ was the second-most selected response (38%). For the regression analysis, the overall modal category /æ/ was selected as the baseline category for comparison purposes.

For /ɑ/ versus /æ/ comparisons of responses to PF /a/, no statistically significant language differences were revealed (NoExp versus ModExp OR=0.92, $p=0.61$, ModExp versus HiExp OR=1.15, $p=0.34$, NoExp versus HiExp OR=1.06, $p=0.66$). However, for the OR of /ɛ/ versus /æ/ assimilation, a significant language experience was revealed (NoExp versus ModExp OR=0.555,$p=0.0096$; ModExp versus HiExp OR=13.286, $p<0.0001$; No Exp versus HiExp OR=7.371, $p<0.0001$). Results suggest a significant effect of context on participants' choosing /ɑ/ over /æ/ in assimilating PF /a/ (OR=2.58, $p<0.0001$). That is, the estimated odds of choosing /ɑ/ over /æ/ in bilabial context were 2.58 times the odds of choosing /ɑ/ over /æ/ in alveolar context. No significant context effect was found for choosing /ɛ/ over /æ/ (OR =0.654, $p>0.0626$).

D. Perceptual assimilation of back PF vowels /o/ and /u/

PF /o/ revealed a significant effect of language experience in perceptual assimilation $[\chi^2(4)=47.16,\ p<0.0001]$ in both comparisons between NoExp and ModExp groups and between ModExp and HiExp groups. A significant consonantal context effect $[\chi^2(4)=18.36,\ p=0.0001]$ was revealed, as well as an interaction $[\chi^2(2)=11.98,\ p=0.0175]$ between language experience and consonantal context. Although it was expected that this vowel would be perceived as most similar to AE /o/ by all groups, the NoExp group assimilated PF /o/ more often to AE /u/ than to AE /o/. The modal category and the second most frequently chosen response reversed themselves with moderate experience. In the HiExp group, listeners had learned to assimilate PF /o/ as most similar to AE /o/. Using AE /o/ as the reference group, NoExp participants were significantly more likely to choose AE /u/ over AE /o/ when compared to the ModExp group (bilabial context: OR=10.07, $p<0.0001$; alveolar context: OR=3.82, $p<0.0001$). Similarly, the ModExp group compared to the HiExp group was significantly more likely to choose /u/ versus /o/ (bilabial context: OR=29.66, $p<0.0001$; alveolar context: $p<0.0001$[7]), as were the NoExp group versus the HiExp group (bilabial context: OR=298, $p<0.0001$; alveolar context: $p<0.0001$. The median ratings for modal responses to PF /o/ were 6 for all three language groups. A context effect was shown by the NoExp group, who assimilated PF /o/ to AE /u/ more often in bilabial context than alveolar context $[\chi^2(1)=17.83,\ p<0.0001]$ but not for the ModExp group $[\chi^2(1)=0.0998,\ p=0.7520]$. The HiExp group assimilated 98% of the PF /o/ stimuli to AE /o/, with no PF /u/ responses in alveolar context; thus no regression analysis was performed for a context effect for the HiExp group.

PF /u/ was perceptually assimilated primarily to AE /u/ and to AE /ʲu/ on a minority of trials (see Table I). Although significant effects of language experience $[\chi^2(4)=27.01,\ p<0.0001]$ and consonantal context PF /u/ $[\chi^2(2)=7.53,\ p<0.0232]$ were shown for PF /u/, statistical analyses of all context and language group comparisons were not significant (for /u/ versus /ʲu/ for NoExp versus ModExp $[\chi^2(1)=0.0002,\ p=0.99]$, ModExp versus HiExp $[\chi^2(1)=0.0000,\ p=1]$ and NoExp versus HiExp $[\chi^2(1)=0.0000,\ p=1]$), probably due to the low rate of /ʲu/ responses. Eight of the 13 HiExp listeners perceptually assimilated PF /u/ to AE /u/ more often in alveolar context than in bilabial, and five assimilated PF /u/ to AE /u/ less often in alveolar context than in bilabial context. The median ratings for PF /u/ as an exemplar of the AE response /u/ were a mean of 7 for NoExp, decreasing to 4 for ModExp and increasing to 6 for HiExp.

E. Perceptual assimilation of front rounded PF vowels /y/ and /œ/

To determine whether PF front rounded vowels were assimilated to AE front or back vowels (Question 1), responses to stimuli containing PF /y/ and /œ/ were collapsed. AE front unrounded vowel responses (/i/, /ɪ/) were combined, central vowels (/ʌ/, /ɝ/) were combined, and back rounded vowels (/u/, /ʲu/, /ʊ/, /o/) were combined. When presented with PF front rounded vowels, 4% of the NoExp group's responses were front AE vowels, 1% were central, whereas 95% were back vowels. The 4% of front vowels chosen by NoExp were primarily due to one listener assimilating all /y/ tokens in bilabial context to /i/ and by one to three front vowel responses (out of 18) by a minority of listeners. Similarly, the ModExp group assimilated 1% of the front rounded vowels to front vowels, 1% to mid, and 98% to back vowels. The HiExp group categorized no front rounded vowels as AE front vowels and 88% as back vowels. Central vowels, primarily rhotacized /ɝ/, accounted for 12% of HiExp responses. Thus, the large majority of listeners perceived front rounded vowels as most similar to AE back vowels.[8] Hence, the analysis will focus on assimilation of PF front versus back rounded vowels.

An overview of perceptual assimilation results in each consonantal context is provided in Tables II and III, which display a matrix of the PF front and back rounded vowels presented to the AE listeners (left column in each context) and the AE vowels to which they were perceptually assimilated (/ʲu/, /u/, /i/, /ʊ/, /o/, /ʌ, /ɝ/) for at least 10% of responses by at least one experience group in one consonantal context. Within each consonantal context (bilabial in Table II, and alveolar in Table III), the second column lists the language experience groups. The figures indicate the percentage of trials (out of 234 opportunities per context) that a particular AE response was chosen by the group. The median rating, in parentheses below the response percentage, indicates the median of goodness ratings from 1 (most foreign sounding) to 9 (most AE sounding) for the trials in which the modal response category was selected.

For the front rounded PF /y/, an overall language experience effect $[\chi^2(6)=43.43,\ p<0.0001]$ and an overall con-

TABLE II. Matrix of PF vowels, /y, œ, u, o/ perceptually assimilated to AE vowels by AE listeners with no French experience (NoExp), moderate French experience (ModExp), and extensive formal+immersion French experience (HiExp) in bilabial context: Percent chosen for each response and median goodness ratings (in parentheses) are presented for each vowel. For each AE vowel stimulus, only responses chosen on at least 10% of the trials (i.e., 23 responses out of 234 possible) in at least one consonantal context by at least one experience group are listed. [Total number of responses per vowel=234 (i.e., 18 judgments per vowel per context by 13 participants in each group).]

PF vowels, bilabial context	Language experience	American English vowels						
		ʲu	u	i	ʊ	o	ʌ	ɝ
y	NoExp	80	7	12				
		(6)	(5)	(4)				
	ModExp	85	13	0.4				
		(3)	(3)	(2)				
	HiExp	72	28					
		(3)	(3)					
œ	NoExp		34		38	8	8	1
			(6)		(6)	(6)	(5)	(7)
	ModExp		11		65	6	12	
			(3)		(4)	(2)	(4)	
	HighExp		3		60	2	8	27
			(4)		(6)	(4)	(4)	(5)
u	NoExp	6	90					
		(4)	(7)					
	ModExp	3	85			4		
		(3)	(4)			(3)		
	HiExp	1	78			13		
		(5)	(6)			(4)		
o	NoExp		62			24		
			(7)			(7)		
	ModExp		18			71		
			(4)			(6)		
	HiExp		1			99		
			(4)			(6)		

text effect [$\chi^2(6)=42.37$, $p<0.0001$] were revealed.[9] As indicated in Table I, significantly more /ʲu/ responses were selected by the ModExp group than by the NoExp group [$\chi^2(1)=23.83$, $p<0.0001$] and by the HiExp group [$\chi^2(1)=15.26$, $p<0.0001$]. The significant experience by context interaction [$\chi^2(6)=22.50$, $p<0.0001$] in the perceptual assimilation of /y/ reflected a significant language experience effect in bilabial context but not in alveolar context. In bilabial context, the estimated OR of selecting AE /u/ versus /ʲu/ was statistically significant for the participants with ModExp when compared to the estimated OR of participants with NoExp selecting AE /u/ versus AE /ʲu/ (OR=1.76, $p=0.08$). Similarly, the estimated OR of selecting AE /u/ versus AE /ʲu/ was significant for the participants with HiExp when compared to the estimated OR of participants with ModExp selecting AE /u/ over /ʲu/ (OR=2.59, $p<0.0001$). Moreover, in bilabial context, participants in the HiExp group chose AE /u/ over /ʲu/ significantly *more* often than participants in the NoExp group OR=4.59, $p<0.0001$). In alveolar context no significant language experience effect was revealed for /y/ (NoExp versus ModExp OR=0.71, $p=0.11$; ModExp versus HiExp OR=1.67, $p=0.95$; NoExp versus HiExp OR=1.18, $p=0.40$).

The consonantal context effect [$\chi^2(3)=45.58$, $p<0.0001$] was evident in that listeners selected /ʲu/ more often in bilabial context than in alveolar. Conversely, AE /u/ was selected in response to PF /y/ more often in alveolar context than in bilabial. The context effect for PF /y/ was smaller for the more experienced groups; differences between alveolar and bilabial contexts for PF /y/ assimilated to AE /u/ were 24%, 9%, and 6% for NoExp, ModExp, and HiExp, respectively, and 15%, 14%, and 11% for PF /y/ assimilated to AE /ʲu/. When experience was treated as an ordinal rather than a nominal variable, it was estimated that the OR comparing alveolar to bilabial context decreased by 52% with each level of experience ($p<0.0001$).

In response to the Levy and Strange (2008) finding that NoExp listeners confused /i-y/ in bilabial context, the AE /i/ responses to PF /y/ were examined relative to the modal AE /ʲu/ response. Individual data suggest that the higher odds of selecting /i/ in bilabial context than alveolar was primarily due to one NoExp participant's assimilation performance. This participant assimilated /y/ to /i/ 100% in bilabial context and 0% in alveolar context. All other NoExp participants' modal responses to /y/ were back vowels. However, their nonmodal responses revealed that PF /y/ was perceptually

TABLE III. Matrix of PF vowels, /y, œ u, o/ perceptually assimilated to AE vowels by AE listeners with no French experience (NoExp), moderate French experience (ModExp), and extensive formal+immersion French experience (HiExp) in alveolar context: Percent chosen for each response and median goodness ratings (in parentheses) are presented for each vowel. For each AE vowel stimulus, only responses chosen on at least 10% of the trials (i.e., 23 responses out of 234 possible) in at least one consonantal context by at least one experience group are listed. [Total number of responses per vowel=234 (i.e., 18 judgments per vowel per context by 13 participants in each group).]

PF vowels, alveolar context	Language experience	American English vowels						
		ʲu	u	i	ʊ	o	ʌ	ɜ˞
y	NoExp	65	31	1				
		(4)	(6)	(7)				
	ModExp	71	24	1				
		(3)	(4)	(2)				
	HighExp	61	34					
		(2)	(4)					
œ	NoExp		59		17	17		
			(6)		(5)	(6)		
	ModExp		23		40	25	5	1
			(4)		(3)	(4)	(2)	(4)
	HighExp		9		61	2	8	20
			(4)		(5)	(4)	(4)	(6)
u	NoExp	9	84			1		
		(4)	(6)			(6)		
	ModExp	15	75			2		
		(3)	(4)			(4)		
	HighExp	5	91					
		(3)	(6)					
o	NoExp		43			41		
			(6)			(6)		
	ModExp		19			69		
			(4)			(5)		
	HighExp					98		
						(6)		

assimilated to AE /i/ in bilabial context on 17% of trials by two participants and on 6% of trials by two other participants. In alveolar context, two participants perceptually assimilated PF /y/ to AE /i/ in 6% of the trials. The NoExp group's responses to /y/ were not significantly more likely to be /i/ (as opposed to /ʲu/) than those of the ModExp Group, for whom only 7% of responses to /y/ were /i/ (OR=1.37, $p=0.084$). Because none of the HiExp selected /i/ as a response choice, the regression model could not examine whether the odds were higher of an individual in the NoExp or in the ModExp group to assimilate /y/ to /i/ than those of an individual in the HiExp group to do so. Thus, a chi-square analysis was performed, comparing experience and choosing /i/ (versus "not /i/") as a response. The statistically significant $[\chi^2(1)=467.00, p<0.0001]$ results suggest a dependence between the level of language experience and choosing AE /i/ as the response to PF vowel /y/.

Internal consistency of /y/ was not significantly different $[F(1,545)=0.28, p=0.5996]$ between listeners in the NoExp group (87% in bilabial, 76% in alveolar) and ModExp group (91% for bilabial and 73% in alveolar). However, consistency was significantly higher with extensive experience compared to moderate experience $[F(1,545)=5.05, p=0.0277]$ and significantly different $[F(1,545)=7.70, p=0.007]$ between NoExp and HiExp groups (95% in bilabial and 78% in alveolar). This suggests that with extensive experience, the listeners had generally selected a category to which they assimilated most of the /y/ tokens. The consonantal context effect was not found to be significant for internal consistency $[F(1,545)=0.03, p=0.8593]$, suggesting that individuals did not respond in a more or less consistent manner as a function of whether PF /y/ appeared in bilabial versus alveolar context.

For PF /œ/, a significant overall language experience effect was revealed $[\chi^2(12)=307.32, p<0.0001]$, with comparisons of estimated odds of response choices between the NoExp and ModExp groups, as well as those between the ModExp and HiExp groups, reaching statistical significance. PF /œ/ was perceptually assimilated to more AE categories than was /y/. For the NoExp group, in fact, when consonantal contexts were combined, no AE category was selected more than 50% of the time in response to PF /œ/; thus comparisons of modal choice AE /ʊ/ versus AE /u/, AE /ʊ/ versus AE /o/, and AE /ʊ/ versus AE /ɜ˞/ were performed.

In the /u/ versus /ʊ/ comparison, the odds of a participant in the ModExp group choosing AE /u/ over AE /ʊ/ in response to PF /œ/ were estimated to be 17% of the odds of an individual in the NoExp group choosing AE /u/ over AE /ʊ/ (OR=0.17, $p<0.0001$). For the ModExp group, the estimated odds of choosing AE /u/ rather than AE /ʊ/ were 392% of the odds of an individual in the HiExp group choosing /u/ rather than /ʊ/ (OR=3.92, $p<0.0001$). Similarly, in a comparison of /o/ selection as opposed to /ʊ/, the estimated odds of a participant with NoExp selecting /o/ over /ʊ/ were 1.56 times the odds of a participant with ModExp selecting /o/ over /ʊ/ (OR=1.56, $p=0.0089$), and the odds of a participant with ModExp choosing /o/ over /ʊ/ were estimated to be 10.87 times the odds of a participant with HiExp choosing /o/ over /ʊ/ (OR=10.87, $p<0.0001$). And finally, for the group with NoExp, the odds of choosing /o/ over /ʊ/ were 19 times the odds of a participant with HiExp choosing /o/ over /ʊ/ (OR=0.19, $p<0.0001$). For the HiExp group, the second most frequent response category was the rhotacized vowel /ɜ˞/ as in "herd" (24%), a response selected virtually only by this group. The estimated OR of a participant in the NoExp group selecting /ɜ˞/ over /ʊ/ versus the odds of a participant in the ModExp group choosing /ɜ˞/ over /ʊ/ were not statistically significant (OR=3.8, $p<0.27$). However, the estimated odds that an individual in the ModExp Group versus an individual in the HiExp group would select /ɜ˞/ rather than /ʊ/ were statistically significant (OR=0.01, $p<0.0001$), as they were only 1% as large as the estimated odds that an individual in the HiExp Group would select /ɜ˞/ over /ʊ/. Similarly, for an individual in the NoExp Group, the estimated odds of choosing /ɜ˞/ rather than /ʊ/ were only 3.8% as high as the estimated odds that an individual in the HiExp group would choose /ɜ˞/ over /ʊ/ (OR=0.038, $p<0.0001$). In the comparison of AE /o/ versus the reference category AE /ʊ/ responses to PF /œ/ for the NoExp group, the estimated odds of choosing AE /o/ rather than AE /ʊ/ were 19 times (1900% of) the odds of a participant with HiExp choosing /o/ rather than /ʊ/ (OR=19.5, $p<0.0001$). For the ModExp group, the estimated odds of choosing AE /o/ rather than AE /ʊ/ were 11 times the odds of an individual in the HiExp group choosing AE /o/ rather than AE /ʊ/ (OR=11.05, $p<0.0001$). The median goodness rating of the modal responses to PF /œ/ was 5 for the HiExp group, 4 for the ModExp group, and relatively high (6) for the NoExp group.

Responses to PF /œ/ also varied significantly as a function of consonantal context [$\chi^2(6)=113.9$, $p<0.0001$]. The AE /u/ response was less frequently chosen in the bilabial condition than in alveolar by all groups. Conversely, more AE /u/ responses were selected by all groups in bilabial than in alveolar context. The odds of choosing AE /u/ rather than /ʊ/ in bilabial context were 26.5% of the odds of choosing AE /u/ rather than /u/ in alveolar context (OR=0.265, $p<0.0001$). The odds of assimilating PF /œ/ to AE /o/ rather than to /ʊ/ in bilabial context were 0.19 times (i.e., 19%) ($p<0.0001$) the odds of choosing AE /o/ over AE /ʊ/ in alveolar context. Thus, the odds of an individual with HiExp choosing AE /o/ rather than AE /ʊ/ were approximately 5.3 (530%) times larger than the odds in alveolar context. However, the odds of choosing AE /ɜ˞/ rather than /ʊ/ were not significantly different (OR=1.36, $p>0.05$) in bilabial versus alveolar context. The experience-context interaction was not significant for /œ/ [$\chi^2(12)=6.94$, $p=0.862$]. A trend toward a decreased context effect with experience was noted (e.g., the differences in response percentages to /œ/ in bilabial versus alveolar context for AE /ʊ/ responses were 21%, 25%, and 1% and for /ʊ/ were 25%, 12%, and 6% for the NoExp, ModExp, and HiExp groups, respectively); however, these decreases were not statistically significant ($p=0.20$).

Internal consistency in perceptual assimilation of /œ/ revealed a significant effect of language experience [$F(1,545)=8.24$, $p=0.0006$.], but no consonantal context effect [$F(1,545)=2.29$; $p=0.1348$.]. The NoExp and ModExp groups demonstrated the lowest consistency for any vowel (NoExp=58% in bilabial and 76% in alveolar; ModExp =75% in bilabial and 57% in alveolar), suggesting that individual listeners selected several categories in response to /œ/ stimuli. The HiExp group, on the other hand, demonstrated high internal consistency (90% in bilabial and 82% in alveolar), suggesting that most /œ/ stimuli were assimilated to the majority of listeners' particular modal category. Planned comparisons indicated no significant difference between the NoExp and ModExp groups [$F(1,545)=0.00$, $p=0.9938$] but a significant difference in internal consistency between ModExp and HiExp [$F(1,545)=12.33$, $p=0.0008$].

IV. DISCUSSION

The main findings for perceptual assimilation of PF /y/ by AE naïve listeners and L2 French learners can be summarized as follows: (a) For all language groups, PF /y/ was perceived as most similar to the AE palatalized vowel /ʲu/ or to /u/. A language experience effect/interaction was found: In bilabial context, PF /y/ was heard most often as relatively similar to AE /ʲu/ by L2-learners with formal education, less often so by naïve listeners, and least often so by listeners with formal + immersion experience. In alveolar context, listeners perceptually assimilated PF /y/ to AE /ʲu/ or /u/ similarly, despite their different language backgrounds. (b) A significant consonantal context effect was revealed with more /ʲu/ responses in bilabial context than in alveolar context. In bilabial context, /ʲu/ responses were greatest for naïve listeners, smaller for listeners with just formal instruction, and smallest for listeners with extensive experience. In alveolar context, a trend in the same direction was noted but did not reach statistical significance. (c) Naïve listeners and listeners with formal experience were relatively consistent in selecting their modal response to PF /y/. With extensive formal and immersion experience, listeners had more or less settled on their particular response.

The main findings regarding perceptual assimilation of the mid front rounded PF vowel /œ/ were the following: (a) PF /œ/ was perceived most often as similar to AE /u/ by naïve listeners. Listeners with formal French experience perceived /œ/ as similar to AE /ʊ/, and individuals with extensive formal and immersion French experience perceived PF /œ/ as most similar to AE /ʊ/ or /ɜ˞/. (b) A consonantal context effect was evident with listeners in all groups perceiving PF /œ/ as similar to AE /ʊ/ more often in bilabial context and

as similar to AE /u/ more often in alveolar context. (c) Individual listeners gave scattered responses to PF /œ/, perceiving this vowel as most similar to several different AE vowel categories (e.g., AE /ʊ, u, o, ʌ, ɝ/. Assimilation patterns were scattered within and across naïve listeners, but with extensive experience, listeners settled on the particular vowel to which they assimilated PF /œ/. In addition, for all vowels combined, assimilation was most internally consistent with extensive language experience and in bilabial context.

The overall language experience effect supports the general finding that adults are capable of continued L2 perceptual learning of vowels in adulthood (e.g., Flege and Hillenbrand, 1984; Gottfried, 1984; Levy and Strange, 2008). L2 phonological learning occurs both in the classroom and with extensive classroom and immersion experience, but some vowels are less learnable than others. The finding that consonantal context affects perceptual assimilation patterns in L2 vowel learning is generally consistent with previous discrimination studies (Gottfried, 1984; Levy and Strange, 2008) but has not been explored in previous perceptual assimilation studies and thus requires replication and further discussion.

A. Effects of language experience on PF front rounded vowels

Returning to Research Question 1, L2-learners' perceptual assimilation of PF front rounded vowels to back AE vowels, despite the PF vowels being acoustically more similar to AE front vowels, replicates work on German vowels (Polka, 1995; Strange *et al.*, 2007) and was predicted from discrimination difficulties with the PF /u-y/ contrast in earlier studies (Gottfried, 1984; Levy and Strange, 2008). In response to Questions 2 and 3, an effect of language experience had not been predicted for PF /y/ but had been predicted for PF /œ/, and more assimilation to PF /u/ had been predicted in alveolar than in bilabial context. The expectation of /œ/ revealing a language experience and context effect was generally borne out. The expectation of PF /y/ not revealing a language experience effect was found to be true in alveolar context but not in bilabial. In bilabial context, /y/ is not an appropriate variant of the AE /u/. Despite this, approximately one-third of the listeners with extensive experience had "phonologized" /y/ to their AE /u/ category, perceiving /y/ consistently as most similar to /u/.

The PAM-L2 (Best and Tyler, 2007) predicts that perceiving PF /y/ as most similar to AE /ʲu/ rather than to AE /u/ will be more advantageous to an L2-learner for discriminating the /u-y/ contrast in that pairing a /ʲu/-like PF /y/ with a /u/-like PF /u/ would result in two-category or category-goodness assimilation rather than single-category or less differentiated category-goodness assimilation. Thus, the language experience effect found in bilabial context for very experienced listeners, with fewer AE /ʲu/ responses and more AE /u/ responses to PF /y/, predicts more discrimination errors than for listeners with less experience or naïve listeners.

Levy and Strange (2008) found less accurate discrimination by individuals with immersion experience than by listeners with no experience. Similarly, in the present study, the HiExp group assimilated /y/ less often to /ʲu/ than did the NoExp group and more often to /u/ than the NoExp group, predictive of more discrimination difficulties. Levy and Strange (2008) did not test listeners with just formal experience, but the present finding of more /ʲu/ responses by these listeners would predict that listeners with only formal experience would fare better in discrimination than listeners with no or extensive immersion experience.

One could speculate that the higher number of /ʲu/ responses by the ModExp group may be a reflection of the orthographic mapping learned in introductory French classes, heightening these learners' awareness of the differences between /u-y/ (Burnham and Mattock, 2007). On the other hand, orthography could also contribute to the /u-y/ confusions, as PF /y/ is spelled as *u* (whereas PF /u/ is spelled as *ou*). One might further hypothesize that with extensive exposure to the PF /u-y/ contrast, listeners may cease to try to distinguish this difficult contrast. That is, the fewest AE /ʲu/ responses for PF /u/ by listeners with extensive immersion experience may point to a sort of "learned helplessness" (Seligman *et al.*, 1968) for the difficult /u-y/ pair, the development of a sense of failure that may be detrimental to language learning (Williams *et al.*, 2004). The absence of a language experience effect in alveolar context, characterized by no overall increase in /ʲu/ responses with experience, is consistent with Gottfried's (1984) and Levy and Strange's (2008) findings of poor PF /u-y/ discrimination in alveolar context, even with French immersion experience, but is not consistent with Flege and Hillenbrand's (1984) report of excellent discrimination of PF /u-y/ in alveolar context.

Assimilation patterns for PF /œ/ hold more promise for perceptual learning with French experience than do patterns for /y/. With formal instruction (ModExp), overall modal responses (/u/ and /ʊ/) reversed, with /ʊ/ being most frequently chosen. For HiExp, rhotacized vowel /ɝ/ was the second most frequent response. The difference in assimilation patterns for PF /œ/ across NoExp and ModExp groups suggests that classroom language experience may be associated with more accurate discrimination for contrasts involving PF /œ/. All comparisons involving HiExp listeners demonstrate perceptual assimilation differences from the less experienced groups, suggesting a difference in phonetic representation with L2 immersion. Consistent with this finding, Levy and Strange (2008) demonstrated that discrimination of PF /œ-u/ was more accurate for L2-learners with immersion experience. The PAM-L2 might attribute the learning of this contrast in part to the high frequency of /œ-u/ minimal pairs (e.g., deux /dœ/ "two" versus doux /du/ "soft/sweet") in dense phonological neighborhoods that contribute to the communicative relevance of learning the contrast. Further studies comparing discrimination by individuals with formal versus immersion experience should shed light on the sequence of discrimination changes in the course of L2-learning (see Levy, 2004).

B. Effects of consonantal context on PF front rounded vowels

As had been predicted, the consonants surrounding front rounded vowels affected assimilation patterns for L2-learners, with more tokens assimilating to /u/ in alveolar con-

text than in bilabial context. In the present study, both PF /y/ and /œ/ perceptually assimilated to AE /u/ almost twice as often in alveolar context than in bilabial context. This may be attributed, in part, to the greater frequency and possibly the more phonemic status of the palatalized /ju/ following bilabials (e.g., "beauty") than following alveolars in AE dialects. In alveolar context, e.g., in "tune," most American dialects have lost the glide preceding the /u/, although exceptions remain, primarily in southern dialects (Phillips, 1981).

Clearly, AE perceptual assimilation of PF vowels cannot be predicted entirely on the basis of the acoustic similarities of French vowels as measured by midsyllable formant frequencies. As shown in Fig. 1, PF /y/ is much closer in acoustic space to PF /i/ than to PF /u/. Yet, even in bilabial context, AE listeners overwhelmingly perceived PF /y/ as most similar to back rounded or palatalized back AE vowels. Instead, explanations must rely on AE listeners' perceptual categorization of French vowels based on their AE phonological system. A developmental linguistic explanation might be the redundancy of the "roundedness" feature in AE. From infancy, AE monolinguals learn to equate roundedness with "backness," as every AE rounded vowel is a "back" vowel (at least at an abstract level of representation) and mid to high back vowels are always rounded. This explanation alone, however, does not account for why the "redundancy effect" would be stronger in alveolar context than in bilabial.

A second explanation involves the allophonic variation of back vowels in AE. The bottom graph in Fig. 1 shows that high to mid back AE vowels (/u, o/ but also /ʊ/, not shown on graph) are fronted in alveolar context, i.e., produced with the tongue further forward in the oral cavity (Hillenbrand *et al.*, 2001; Strange *et al.*, 2007). Thus, in English, the /u/ is produced as back rounded /u/ in nonalveolar contexts (e.g., "boom"), but in alveolar context (e.g., "dude"), AE /u/ is a fronted vowel. AE listeners, then, may be more likely to categorize front rounded vowels as AE /u, ʊ, o/ when these vowels are surrounded by alveolar consonants than when they are in other contexts. This explanation would account for the increased number of AE /u/ responses to PF /y/ and /œ/ in alveolar context—the context in which fronting is most extreme.

The bottom graph in Fig. 1 also reveals PF /œ/ as only slightly fronted in alveolar context relative to its position in bilabial context (top graph), but the greater fronting of the AE back vowels causes the PF /œ/ to overlap with the AE /u/ vowel category, while remaining distinct from AE front vowels. Similarly, discriminant analysis by Strange *et al.* (2007) found PF /œ/ more spectrally similar to the (fronted) AE /u/ and /ʊ/ vowels in alveolar context than to AE /u/ and /ʊ/ in bilabial context in sentence materials. Thus, more assimilation of PF /œ/ to AE /u/ in alveolar context than in bilabial context can be understood based on these acoustical data, as can AE listeners' increased discrimination difficulty for PF /œ/ paired with back vowels in alveolar context (Levy and Strange, 2008). With more French experience, listeners tended to assimilate the PF vowel /œ/ primarily to AE /ʊ/ and /ɝ/ in both consonantal contexts. The selection of the rhotacized vowel /ɝ/ response may be due to the lip rounding and raising of the tongue (as occurs for front rounded vowels) that accompanies AE rhotacization.

C. Theoretical implications

Results from this study contribute to the literature indicating that variations in the acoustic realization of vowels as a function of consonantal context affect their perception in an unfamiliar language (Strange *et al.*, 2001; Strange *et al.*, 2004a) and now also in an L2 (e.g., Gottfried, 1984; Levy and Strange, 2008). In the terminology of the PAM (Best, 1995), the consonants surrounding vowels affect to which native vowel a non-native vowel will be assimilated and the goodness of fit to that category. For example, AE listeners perceptually assimilate PF /œ/ to AE /u/ more often in alveolar context than in bilabial context. The PAM, factoring in context, would predict that the /œ/ would be more difficult to differentiate from /u/ in alveolar context than in bilabial, a prediction borne out in Levy and Strange's (2008) study.

The relatively high goodness rating for PF /u/ by the HiExp group in the present study supports Flege's (1987) claim that PF /u/ is perceived as a good instance of AE /u/ and thus might be produced in an equivalent, i.e., accented, manner. In terms of the SLM (Flege, 1995), the data are consistent with category formation in bilabial context but not in alveolar context. The context-specific categorization revealed here suggests an allophonic level of representation (as discussed by Flege, 1995) operating in equivalence classification, such that listeners perceive vowels as "new" or "similar," depending on their phonetic environment. Thus, /y/ could be "equivalent" to AE /u/ in alveolar context and "new" in bilabial. However, the relatively low goodness ratings for /y/ in both contexts for the HiExp group suggest that as L2-learners became familiar with French, they began to discern differences between /y/ and AE vowels.

Evidence suggests that listeners do not encode contrasts in terms of context-independent phonemic units (Pisoni *et al.*, 1994). Such abstract units could not explain the context effects found in the present study and in numerous other studies (e.g., Gottfried, 1984; Levy and Strange, 2008; Strange *et al.*, 2001; 2004a). Clearly, neither an abstract, phonemic analysis nor an acoustic description of L2 segments will adequately predict the way in which an L2 segment is learned. For now, it may be concluded that L2 segments are initially perceived on an intermediate, context-sensitive allophonic level. Learning an L2 ideally involves the formation of new phonological categories, including knowledge about the systematic variations that exist within each L2 category (Flege, 1995). Although perception and production of segments might improve with experience (Flege, 1987; Gottfried, 1984; Levy and Strange, 2008) and with perceptual training (Bradlow *et al.*, 1997; Iverson *et al.*, 2005; Rvachew, 1994), even the most experienced late learners' native phonological knowledge (including language-specific allophonic rules) may continue to influence their L2 perception.

TABLE IV. Statistical significance on comparisons performed for regression analysis (*=significance at the $p=0.05$ level; nonsignificance=ns at the $p=0.05$ level; n/a=not applicable because few responses in any category were other than modal).

Vowel	Comparison	Language experience (in at least one context): NoExp vs ModExp	Language experience (in at least one context): ModExp vs HiExp	Language experience (in at least one context): NoExp vs HiExp	Consonantal context	Interaction
i	n/a	n/a	n/a	n/a	n/a	n/a
ɛ	ɛ vs e	ns	ns	ns	ns	ns
	ɛ vs æ	*	ns	*	ns	ns
a	æ vs ɑ	ns	ns	ns	*	ns
	æ vs ɛ	*	*	*	ns	ns
o	o vs u	*	*	*	*	*
u	ʊ vs ^{j}u	n/a	n/a	n/a	n/a	n/a
y	^{j}u vs u	*	*	*	*	*
œ	ʊ vs u	*	*	*	*	ns
	ʊ vs o	*	*	*	*	ns
	ʊ vs ɜ˞	ns	*	*	ns	ns

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APPENDIX: REGRESSION COMPARISONS AND STATISTICAL SIGNIFICANCE

Table IV shows the comparisons using the regression analysis and their statistical significance or nonsignificance.

[1]The front rounded vowels /ø/ and /œ/ are almost never contrastive in PF. For the present purposes, /œ/ will represent the midfront rounded vowel.

[2]In cross-speaker tasks, the speaker differs across A, X, and B tokens; thus, listeners must make judgments on the basis of speaker-independent categorical representations of the stimuli.

[3]One of the PF speakers' stimuli had also been used in Levy and Strange (2008), but an additional token of each of her vowels plus three tokens each of /o/ and /ɛ/ were used here. Of the 39 listeners in this study, one HiExp participant had also participated in Levy and Strange. However, three years had passed, thus learning effects were expected to be minimized.

[4]Although listeners in the HiExp group were generally of a more advanced age than those in the other groups, it is not expected that this affected the results, as the HiExp group performed similarly to the other groups on the "control" vowel /i/ and on other vowel stimuli.

[5]To determine whether F3, which is lowered with lip rounding, might have contributed to the perceptual patterns, F1 values were subtracted from F2 values and F2 values from F3 values for /y/, /u/, and /i/ in each context (e.g., F3−F2=1.1 bark for /y/, 2.3 bark for /i/, and 7.7 bark for /u/ in bilabial context). Results indicated that even taking F3 into consideration, /y/ is acoustically more similar (i.e., closer in vowel space) to /i/ than to /u/ in PF.

[6]The acoustical data from four tokens of vowels produced by three PF and three AE female speakers in the study of Strange *et al.* (2007) reveal more separation between PF /u/ and PF /o/ vowels and less of a shift in F1 between PF and AE vowels than in the present study; thus the differences seen here in F1 may be a function of individual differences related to the vocal tract size. In the present study, the HiExp listeners assimilated PF /o/ to AE /o/ on 98% of trials (as opposed to naïve listeners, who assimilated PF /o/ to AE /o/ on 32% of trials and to AE /u/ on 53% of trials), suggesting that with experience, listeners had become skilled at sorting out differences between PF /o/ and /u/, perhaps by reference to point vowels, which also shifted in vowel space.

[7]Fisher's exact test (appropriate for zero-cell counts) was used for comparisons with HiExp groups in alveolar context for PF /o/, as no participant in the HiExp group selected AE /u/ in response to PF /o/ in alveolar context; thus the regression analysis could not be performed.

[8]An argument could be made that if /^{j}u/ had not been a response choice, more AE /i/ responses would have been chosen. Studies that have not used /^{j}u/ as a response alternative in perceptual assimilation have found assimilation of PF /y/ primarily to AE back vowels. For example, Strange *et al.* (2004b) found that naïve listeners assimilated PF /y/ in sentence context to back vowels on 84% of responses. This suggests that without the inclusion of a /^{j}u/ response option, back-vowel responses would have been similar or slightly fewer in number.

[9]When /^{j}u/ and PF /u/ responses were combined and compared to the resulting second-most selected choice, AE /ʊ/, the overall language experience effect was statistically significant [$\chi^2(4)=15.64$, $p<0.0035$], as was the context effect [$\chi^2(2)=20.92$, $p<0.0001$]. However, as /ʊ/ was chosen by fewer than 10% of listeners, comparisons with /ʊ/ may not be meaningful.

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