Cross-language categorization of French and German vowels by naïve American listeners

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American English (AE) speakers' perceptual assimilation of 14 North German (NG) and 9 Parisian French (PF) vowels was examined in two studies using citation-form disyllables (study 1) and sentences with vowels surrounded by labial and alveolar consonants in multisyllabic nonsense words (study 2). Listeners categorized multiple tokens of each NG and PF vowel as most similar to selected AE vowels and rated their category "goodness" on a nine-point Likert scale. Front, rounded vowels were assimilated primarily to back AE vowels, despite their acoustic similarity to front AE vowels. In study 1, they were considered poorer exemplars of AE vowels than were NG and PF back, rounded vowels; in study 2, front and back, rounded vowels were perceived as similar to each other. Assimilation of some front, unrounded and back, rounded NG and PF vowels varied with language, speaking style, and consonantal context. Differences in perceived similarity often could not be predicted from context-specific cross-language spectral similarities. Results suggest that listeners can access context-specific, phonetic details when listening to citation-form materials, but assimilate non-native vowels on the basis of context-independent phonological equivalence categories when processing continuous speech. Results are interpreted within the Automatic Selective Perception model of speech perception. © *2009 Acoustical Society of America.*
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I. INTRODUCTION

A theoretical tenet of current models of non-native and L2 speech perception (Best, 1995; Best and Tyler, 2007; Flege, 1995) is that phonetic similarities of L1 and L2 segments can, in significant part, predict relative difficulties that naïve listeners and L2 learners will have in distinguishing non-native phonetic segments. However, researchers differ in how they determine L1/L2 vowel similarities empirically. Some studies have used cross-language comparisons of the acoustic structure of vowels, primarily spectral similarity defined by relative locations in a target formant-frequency vowel space (e.g., Flege *et al.*, 1994), whereas others (e.g., Best *et al.*, 2003) refer to (abstract) articulatory-phonetic similarities of L1 and L2 vowels. A growing number of studies have employed direct measures of *perceived* L1/L2 similarities, referred to as cross-language categorization or perceptual assimilation tasks (see Strange, 2007b, for a critique of these techniques).

The present research employed a perceptual assimilation task to examine the perceived similarities of North German (NG) and Parisian French (PF) vowels to American English (AE) vowels by monolingual speakers of New York English (NYE). Of special interest was the perceptual assimilation of NG and PF front, rounded vowels, which are phonologically distinctive in both PF and NG (contrasting with both front, unrounded vowels and back, rounded vowels), but occur only as allophonic variants of back, rounded vowels in AE (Hillenbrand *et al.*, 2001; Strange *et al.*, 2007). Previous research (reviewed below) has produced conflicting results about AE listeners' relative perceptual difficulty with contrasts involving front, rounded vowels in French and German. In addition, research has also documented perceptual problems by AE listeners with other French and German contrasts that are also phonologically distinctive in AE, but that differ phonetically across languages. Thus, in the two studies reported here, naïve listeners were presented the full (oral) vowel inventories of PF (9 vowels) and NG (14 vowels).

Previous cross-language research on French and German vowels has shown that perception by AE listeners varies significantly as a function of both the speaking style in which the stimuli are produced and presented (e.g., lists vs sentences) and the consonantal context in which the vowels occur (Gottfried, 1984; Levy, 2009; Levy and Strange, 2008;

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Strange *et al.*, 2004, 2005). Recent research on the acoustic structure of distributions of PF, NG, and AE vowels produced in different prosodic and phonetic contexts (Strange *et al.*, 2007) has documented language-specific patterns of contextual variation in spectral and temporal structure that lead to significant differences across contexts in the acoustic similarity of many PF and NG vowels relative to AE vowels. Thus, it was expected that L1/L2 perceived similarity relationships would also vary with prosodic and phonetic context. This contextual variation might account, at least in part, for the conflicting results of earlier research on AE listeners' perception of French and German vowel contrasts. In study 1, vowels produced in citation-form disyllables served as the stimuli. In study 2, the stimuli were vowels produced and presented in multisyllabic nonsense words embedded medially in short carrier sentences, with the vowels surrounded by labial and alveolar consonants.

Most studies of perceptual assimilation of non-native vowels by naïve listeners have reported group data for each set of L1 listeners. However, previous studies of AE listeners' perception of NG and PF vowels suggest that there may be significant differences among AE individuals in how NG and PF vowels are perceptually assimilated (Levy, 2009; Levy and Strange, 2008; Strange *et al.*, 2004, 2005). Thus, in both studies presented here, the data are reported in two ways: (1) overall categorization distributions and group median goodness ratings and (2) patterns of perceptual assimilation by individual listeners. The latter analysis allowed the authors to ask questions about differences in assimilation patterns across the two languages (and across contexts in study 2) using repeated measures analyses. However, due to practical considerations, independent groups of AE listeners served as participants in studies 1 and 2; both were drawn from the same NYE dialect group.

II. STUDY 1: GERMAN AND FRENCH VOWELS IN CITATION-FORM UTTERANCES

In the first study, NG and PF vowels were produced and presented in a "neutral" context ([hVbə] for NG vowels and [Vb(ə)] for PF vowels) that minimized coarticulatory influences of preceding and following consonants, while presenting closed syllables in which both tense and lax AE vowels are allowed phonologically. Most previous studies of AE listeners' perception of German and French contrasts presented citation-form monosyllables of the form #V#, CV, or CVC (Best *et al.*, 1996; Flege and Hillenbrand, 1984; Gottfried, 1984; Gottfried and Beddor, 1988; Polka, 1995; Strange *et al.*, 2004) or synthetically-generated #V# or CVC syllable continua (Gottfried and Beddor, 1988; Rochet, 1995). In the studies using CV or CVC syllables, the vowels were preceded and/or followed by alveolar consonants /d, t, s/. Our recent work on the acoustic variability of AE, NG, and PF vowels (Strange *et al.*, 2005, 2007) suggests that perception by AE listeners of back vs front, rounded NG and PF vowels may differ markedly in coronal and non-coronal contexts (see also Levy, 2009; Levy and Strange, 2008) due to the extreme allophonic fronting of AE [uː, ʊ, oʊ] in coronal contexts in most dialects of AE (cf., Hillenbrand *et al.*, 2001). Thus, results of the previous studies may not be representative of assimilation of front, rounded vowels (or indeed other non-native vowels) in general. The results of study 1 using vowels produced in a non-coronal context provided a basis for establishing cross-language perceived similarities of "canonical" NG and PF vowels (cf., Strange *et al.*, 2007) and may be contrasted with results of earlier studies using vowels surrounded by alveolar consonants.

Current models of cross-language and L2 speech perception (Best, 1995; Best and Tyler, 2007; Flege, 1995) are in agreement that, to be predictive of L2 perceptual difficulties, cross-language similarity relationships must be established at a level of description of phonetic segments that includes more detail than transcriptional equivalences or distinctive-feature characterizations of phoneme inventories. In his speech learning model (SLM), Flege (1995) posited that consonant and vowel categories in L1 and L2 are represented at the level of position-sensitive allophones. Best and Tyler (2007) claimed that listeners can be responsive both to phonologically-relevant phonetic information and to within-L1-category phonetic variation. In a perceptual assimilation task such as the one utilized here, categorization of L2 vowels as exemplars of the most similar L1 category by naïve listeners may reflect perceived similarity based on (L1) phonological categories, whereas ratings of category goodness may reflect perceptual attunement to gradient (perhaps language-universal) phonetic differences between L1 and L2 phones.

In the Processing Rich Information from Multidimension Interactive Representations (PRIMIR) model of the development of L1 speech processing, Werker and Curtin (2005) pointed out that performance by infants, children, and adults in speech perception experiments reflects the requirements of the language processing task as well as the initial biases and developmental level of the listener. Under the appropriate stimulus and task conditions, fine-grained, within-category phonetic information is available to adult listeners, even though they demonstrate highly over-learned language-specific patterns of perceptual processing in most online perception situations. In her Automatic Selective Perception model of speech perception, Strange (2006, 2007a, 2009; see also Strange and Shafer, 2008) outlined a similar account of the role of selective perception and attention in L1 and L2 speech perception. By this account, online L1 speech perception by adults is normally accomplished using highly over-learned selective perceptual routines (SPRs). These L1 SPRs enable the listener to extract the most reliable phonologically-relevant information rapidly from the incoming speech stream in order to recover the intended message (i.e., words specified by phonetic sequences), with few or no attentional resources required. However, when asked to differentiate segments that are not phonologically distinctive in the L1, performance may suffer because listeners' automatic L1 SPRs are not attuned to the appropriate phonetic information. Thus, listeners must resort to an attentional mode of perception in order to (learn to) detect the phonetic information that reliably distinguishes the non-native contrasts. This may be especially difficult when an L2 contrast is differentiated along phonetic dimensions that constitute allophonic variations in the L1. However, under relatively constrained stimulus and task conditions, naïve listeners are able to attend to within-L1-category phonetic details and make accurate discriminations. As the stimuli and tasks become more complex, listeners' performance may only reflect categorization on the basis of L1 SPRs.

According to this conceptual scheme, the task given naïve listeners in a perceptual assimilation study of non-native contrasts explicitly directs them to attend to the phonetic details *in relation to* native phonological categories in making their responses. A question of interest, then, is how to characterize the nature of the phonetic information being used and whether it reflects a language-general or a language-specific mode of phonetic processing. If it is the former, the authors might expect that context-specific acoustic and underlying articulatory similarity relationships would be predictive of perceptual similarity patterns. Alternatively, listeners may respond on the basis of systematic patterns of language-specific phonetic variation characterized by L1 allophonic realization rules. The authors might expect, therefore, that categorization responses will reflect the relationship of the non-native segments to L1 phonological categories, in which (noncontrastive) allophonic variants are considered "equivalent" in terms of lexical specification. On the other hand, category goodness ratings might reflect detailed phonetic knowledge about the appropriateness of particular phonetic variants in particular contexts in the L1.

A previous study of AE listeners' perceptual assimilation of NG vowels in [hVp] syllables supports the latter hypothesis (Strange *et al.*, 2004). Front, rounded NG vowels were assimilated primarily to back AE vowels, despite the fact that they were acoustically more similar to AE front vowels or intermediate between front and back AE vowels in this context. However, front, rounded NG vowels were judged to be poorer exemplars of back AE categories than were the back NG vowels. [See Polka (1995) for similar results for Canadian English listeners' assimilation of front vs back, rounded vowels in dVt syllables.] In addition, Strange *et al.* (2004) reported that assimilation patterns for NG vowels with transcriptional counterparts in AE (so-called "similar" vowels) suggested that listeners were sensitive to cross-language differences in the phonetic realization of some (e.g., NG [e:]), whereas others were assimilated as good exemplars of their AE counterparts (e.g., [o:, ɛ]), despite cross-language differences in their relative locations in F1/F2/F3 vowel space.

Fewer data are available on the perceptual assimilation of citation-form French vowels by naïve AE listeners. Based on the *productions* of French [ty] and [tu] by AE L2 learners of French, Flege and Hillenbrand (1984) hypothesized that AE learners did not assimilate French [y] to any AE category, while they initially assimilated French [u] to AE [u]. However, this study did not include a perceptual assimilation task. In this context, AE [u] is highly fronted, which may account for the unexpected finding that inexperienced L2 speakers' productions of [ty] were more similar acoustically to native French speakers' [ty] productions (and identified more accurately by French listeners) than were their productions of [tu] to native French speakers' [tu] productions.

Gottfried (1984) examined discrimination of French vowel contrasts by naïve and experienced AE late L2 learners using a cross-speaker categorial ABX task. Results indicated that naïve listeners performed better on [u/y] and [y/ø] contrasts in #V# than in tVt context; the French [i/y] contrast was not tested. Gottfried (1984) also reported significant discrimination difficulties for naïve AE listeners on [i/e] and [e/ɛ] in both contexts. The poor discrimination of the front, rounded vowels [y/ø] reported by Gottfried (1984) differs from results reported by Best *et al.* (1996) on a single-speaker categorial discrimination test of CV French syllables [sy/sø], which most naïve AE listeners assimilated to two separate AE categories and discriminated with better than 95% accuracy. [See also Best *et al.* (2003) who reported very good discrimination of Norwegian front, in-rounded [sʉ] vs back [su], but less good discrimination of front, unrounded [si] vs out-rounded [sy].]

These discrepant results of perception of front, rounded vowels by naïve AE listeners indicate that performance can vary substantially as a function of stimulus, task, and listener factors, making comparisons across studies difficult. In the present study, the same listeners provided cross-language categorization and goodness ratings of NG and PF vowels produced by a representative speaker of each language, drawn from our earlier work on the acoustic structure of NG, PF, and AE vowels (Strange *et al.*, 2007). Thus, performance by the same naïve AE listeners could be compared directly across languages, with stimulus context and task demands held constant. This allowed the authors to ask the following questions:

(1) How do naïve AE listeners perceptually assimilate front, rounded NG [y:, ʏ, ø:, œ] and PF [y, ø] vowels in citation-form utterances? Specifically, the authors predicted the following.
   (a) Cross-language categorization patterns would reflect context-general spectral similarities of NG and PF front, rounded vowels to AE phonological categories, which include fronted allophones of back, rounded vowels. Despite their acoustic similarity to AE front vowels in this context, NG and PF front, rounded vowels (except for [œ]) would be categorized as more similar to back than to front AE vowels because high to mid, back AE vowels are allophonically fronted in alveolar contexts, whereas front AE vowels are rarely backed.
   (b) Listeners' goodness ratings would reflect their perception of context-specific phonetic differences between front and back, rounded NG and PF vowels; front, rounded vowels would be rated as poorer exemplars than back, rounded vowels of AE back vowels in a non-coronal context. Because PF [y] is more front (higher F2/F3 values) and spectrally closer to PF [i] than NG [y:] is to NG [i:], they also predicted that PF [y] would be considered a poorer exemplar than NG [y:] of AE [u:], or indeed might be judged as an exemplar of AE [i:] in this context by a majority of listeners.
   (c) Based on previous results, they predicted that AE listeners would show little sensitivity to duration differences in spectrally-similar NG [ʏ/ø:].

(2) How consistently are NG and PF mid-high to mid-low, front, unrounded and back, rounded vowels assimilated to their AE transcriptional counterparts? Specifically, they predicted the following.

   (a) NG and PF mid-high to mid-low vowels that are higher (F1 values lower relative to high vowels) in their respective vowel spaces than AE counterparts would not be consistently assimilated to their AE transcriptional counterparts. Strange *et al.* (2004, 2007) reported differences from AE in the relative heights of these vowels for both NG and PF, especially for front vowels [e, ɛ], which may account for previously reported perceptual difficulties.

(3) How are low vowels, NG [ɑː, a] and PF [a], perceptually assimilated to AE vowels? Specifically, they predicted the following.

   (a) If categorized on the basis of spectral similarity, PF [a] would be assimilated more often to AE [æː], while NG [ɑː, a] would be judged as more similar to AE [ɑː, ʌ], respectively.

   (b) Based on previous research, they predicted that duration differences between NG [ɑː, a] would not contribute significantly to differences in perceived similarity for most AE listeners.

A. Method

1. Speakers and stimuli

Productions of one male speaker of NG and of PF were selected from the corpora of three speakers of each language analyzed in an earlier study of NG, PF, and AE vowel productions (Strange *et al.*, 2007). The 27-year-old NG speaker was from Fallingbostel in Northern Germany, while the 37-year-old PF speaker was from Les Mureaux, a Paris suburb. Both were proficient only in their native language and had been in the USA for only a short time. Details of recording procedures are available in the previous publication. For the present study, three tokens of each vowel category were selected and were verified as very good exemplars of each vowel category by a native NG and PF listener. For NG stimuli, vowels were produced in nonsense disyllables ([hVbə] spelled "Hieba, Hibba, Hehba …"), whereas PF vowels were produced by reading words spelled "hVb" but pronounced by PF speakers as /Vb/ with an audible voiced release of the final labial [Vb(ə)]. For a task familiarization procedure, 3 tokens of each of 11 AE vowels [iː, ɪ, eɪ, ɛ, æː, ɑː, ʌ, ɔː, oʊː, ʊ, uː] produced in citation-form [hVbə] disyllables by one of the AE male speakers (a 36-year-old native speaker of NYE dialect) from Strange *et al.* (2007) were also selected.

Figure 1 displays the mid-syllable spectral values (F1/F2 in barks) of the three tokens of each NG vowel (top plot) and each PF vowel (bottom plot) used in the perceptual assimilation tests. For comparison, these vowels are superimposed on ellipses depicting the range of values of 11 AE vowels produced by all three male speakers in citation disyllables from Strange *et al.* (2007). Since the point vowels [i, ɑ/a, u] were similar across the three languages, a comparison of other vowels was presumed to be meaningful with respect to

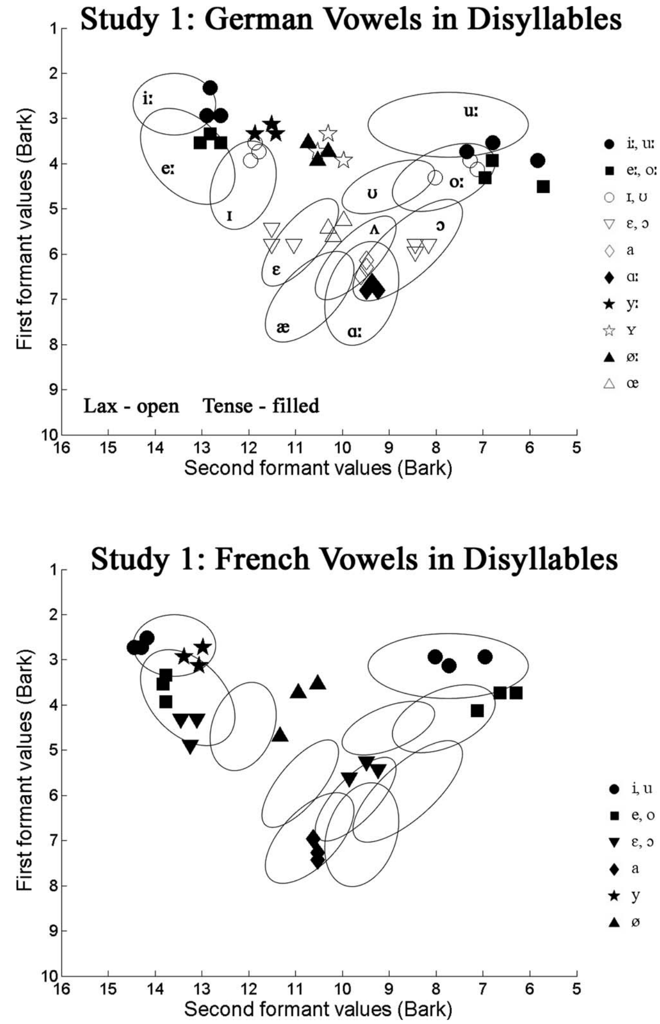

FIG. 1. NG (above) and PF (below) stimuli for study 1 (3 tokens of each vowel), superimposed on ellipses surrounding 11 AE vowels produced by 3 male speakers in citation-form hVb disyllables. For German vowels, short vowels are shown in open symbols, long vowel in closed symbols.

dissimilarities in articulatory postures across the three languages, independent of vocal tract differences.

To quantify spectral similarities to AE vowels, the NG and PF vowel stimuli were submitted to linear discriminant analyses in which the AE vowel corpus (3 speakers × 4 tokens of each vowel) from Strange *et al.* (2007) served as the training set and the NG and PF stimuli served as the test sets. Classification of the NG and PF stimuli, relative to weighted centers of gravity for the 11 AE vowel categories, using F1/F2/F3 bark values as input parameters, can be summarized as follows (see Appendix, Table VI for classification results).

Front, rounded NG and PF vowels were almost all classified as closer to AE front than to back vowels. PF [y] was even more front (higher F2 values) and overlapped completely with AE [iː] in F1/F2 space (see Fig. 1). Second, NG and PF /e/ were located relatively high (low F1 values) and some tokens were classified as AE [iː, ɪ]. Third, PF [ɛ] was also very high (lower F1 values) relative to AE and NG [ɛ], with all tokens classified as AE [eɪ]. Finally, whereas the NG low vowels [ɑː, a] were classified as back AE vowels [ɑː, ʌ], PF [a] was consistently classified as more similar to front AE [æː].

TABLE I. Perceptual assimilation of NG (A) and PF (B) back and front, rounded vowels to AE categories: Study 1—Citation materials. Modal AE V is the AE vowel chosen most often, summing over all 11 AE listeners. Percent is the overall percent of trials on which the modal response was chosen. (Rating) is the overall median goodness rating on modal response trials, summed over listeners. # of Ss is the number of AE listeners (out of 11) selecting a single response on at least 7 of 9 trials.

	Back Vs	Modal AE V	Categorization Percent	(Rating)	# of Ss	Front Vs	Modal AE V	Categorization Percent	(Rating)	# of Ss
(A)	uː	uː	94	(8)	10	yː	uː	77	(4)	8
	oː	oʊ	98	(8)	11	øː	ʊ	53	(2)	4[ʊ], 2[oʊ]
	ʊ	oʊ	65	(7)	4	ʏ	ʊ	62	(4)	5 [ʊ], 2 [uː]
	ɔ	oʊ	37	(4)	2	œ	ɛ	43	(5)	3 [ɛ], 1 [ʌ]
(B)	u	uː	84	(7)	9	y	uː	52	(2)	3 [uː], 1[iː]
	o	oʊ	69	(6)	7	ø	ʊ	48	(3)	3 [ʊ], 1 [oʊ]
	ɔ	ʌ	62	(6)	7 [ʌ], 1 [oʊ]					

2. Procedures and tests

All perceptual tests were performed on a personal computer located in a quiet testing room using a specialized program (PARADIGM ID by Bruno Tagliaferri) that controlled the task and recorded responses. Participants heard stimuli over STAX Professional SR Lambda earphones via a STAX Professional SRM-1/MK-2 amplifier with output set at a prearranged comfortable listening level. In these tests, a trial consisted of the following steps: (1) a stimulus was presented and response alternatives appeared on the screen (11 onscreen "buttons" labeled with hVd key words and IPA symbols), (2) the participant clicked on one of the buttons (categorization response) after which, (3) the same utterance was repeated and a nine-point Likert scale appeared (9 labeled "very American-like" and 1 labeled "very foreign sounding"), and (4) the participant clicked on the Likert scale to indicate the category goodness of the stimulus as an exemplar of the selected AE vowel category. During the NG and PF tests, no feedback was presented.

At the beginning of the experiment, each participant was given a task familiarization test that consisted of five blocks of trials using the AE stimuli. Correct/incorrect feedback was given for blocks 1–3 (11 vowels each). To pass criterion for inclusion in the study, participants could make no more than 2 errors total on block 4 or 5 (22 vowels each/2 tokens of each vowel), with no more than 1 error on any one vowel category. No feedback was given. If participants performed at 100% on block 4, they did not complete block 5.

The NG perceptual assimilation test consisted of 4 blocks of 42 stimuli—3 different tokens of each of 14 vowel categories, randomly ordered separately for each participant. The first block was used for familiarization with the non-native stimuli and calibration of goodness ratings; the data were not included in the final scoring. Blocks 2–4 (nine judgments/vowel; three trials/token) served as the test data. The PF perceptual assimilation test had the same structure (4 blocks of 27 stimuli; 3 different tokens of each of 9 vowel categories). Again, the first block was used for familiarization and was not counted as test data. The order of languages was counterbalanced across participants with a pause between tests.

3. AE listeners

A total of 16 participants completed the AE familiarization task. Five participants were discontinued because of a failure to reach criterion; thus, 11 participants completed the NG and PF tests. None had any experience with French, German, or any other language with front, rounded vowels. Most had taken some foreign language classes in high school or college, but none could converse in any language but English by self-report. They were all current residents of the New York metropolitan area, had been raised in New York or New Jersey, and spoke a "standard" northeastern dialect in which [ɑː/ɔː] are differentiated. The authors can assume that these listeners' vowel spaces resembled those presented in Fig. 1 for AE speakers from the same dialect population. The participants ranged in age from 22 to 54 years of age and reported normal hearing.

B. Results

For the group analysis, overall categorization distributions (summed over 11 participants $\times$ 9 trials = 99 responses/vowel) were computed. For each NG and PF vowel, the modal AE categorization response, the overall consistency in the choice of that modal category as a percentage of total trials, and the overall median[1] goodness rating for trials on which the modal response alternative was selected were computed. For analyses of individual data, each listener's responses to each NG and PF vowel were designated as categorized (the same AE response chosen on at least 7 out of 9 trials)[2] or uncategorized. The number of listeners (Ss) with categorized responses for each NG and PF vowel was tallied.

1. Back and front, rounded vowels

Group categorization results for back (columns 1–4) and front (columns 6–9), rounded vowels are shown in Table I. In addition, the number of AE listeners (out of 11) who showed consistent categorization of each vowel is given (columns 5 and 10), with vowels indicated in brackets when AE vowels in addition to the group modal vowel were selected consistently by some individuals.

Regarding the back, rounded vowels, both group and individual data indicate that NG [uː, oː] were consistently categorized as most similar to their AE transcriptional coun-

TABLE II. Perceptual assimilation of NG (A) and PF (B) front, unrounded and low vowels to AE categories: Study 1—Citation materials. Modal AE V is the AE vowel chosen most often, summing over all AE listeners. Percent is the overall percent of trials on which the modal response was chosen. (Rating) is the overall median goodness rating on modal response trials, summed over listeners. # of Ss is the number of AE listeners (out of 11) selecting a single response on at least 7 of 9 trials.

	Front NG	Modal AE V	Categorization Percent	(Rating)	# of Ss	Low NG	Modal AE V	Categorization Percent	(Rating)	# of Ss
(A)	iː	iː	91	(7)	10	ɑː	ɑː	87	(7)	10
	eː	eɪ	85	(7)	10	a	ɑː	61	(7)	5 [ɑː] 1 [ʌ]
	ɪ	ɪ	87	(8)	9					
	ɛ	ɛ	95	(7)	10					
	Front PF	**Modal AE V**	**Categorization Percent**	**(Rating)**	**# of Cons. Subjects**	**Low PF**	**Modal AE V**	**Categorization Percent**	**(Rating)**	**# of Ss**
(B)	i	iː	96	(8)	11	a:	ɑ	80	(6)	8 [ɑː]
	e	eɪ	80	(7)	9					
	ɛ	ɛ	82	(6)	8 [ɛ] 1 [eɪ]					

terparts by almost all the listeners and were judged as very good exemplars of those categories. PF [u, o] were somewhat less consistently assimilated to their AE counterparts within and across listeners, with lower median goodness ratings. In contrast, NG [ʊ, ɔ] were not consistently assimilated as examples of their transcriptional counterparts in AE, although a few listeners categorized them both as AE [oʊ]. A majority of the listeners assimilated PF [ɔ] to AE [ʌ].

Turning to the front rounded vowels, the group data indicate somewhat less consistency within and across listeners in how these vowels were categorized, relative to the back vowels. However, except for NG [œ], the group modal response was an AE back vowel. Summing over all AE back vowel responses, NG [y:, ø:, ʏ] were perceptually assimilated to AE back vowels on 99%, 96%, and 89% of trials, respectively, whereas NG [œ] was assimilated to AE back vowels 52% of the time. PF [y] and [ø] were assimilated to AE back vowels 84% and 95% of the time, respectively. Thus, except for NG [y:], the front, rounded vowels could be considered uncategorizable back vowels for many AE listeners. Only one AE listener consistently heard PF [y] as most similar to AE [i:]. None of the listeners heard NG [y:] as most similar to a front AE vowel and eight listeners assimilated it consistently to AE [u:]. Comparing assimilation of NG [y:] and PF [y], significantly more subjects consistently categorized NG [y:] as AE [u:] (8 vs 3; significant by a Fisher's Exact test, $p=0.04$, one-tailed test). Perceptual assimilation patterns for NG [ø:, ʏ], which were spectrally very similar but differed in duration, gave only weak evidence that vowel duration was used by AE listeners in categorization decisions; both were assimilated primarily to short AE [ʊ].

An inspection of overall goodness ratings (columns 4 and 9) shows that, on average, NG and PF front, rounded vowels were considered poorer exemplars of AE back vowels than were NG and PF back vowels except for NG [œ, ɔ]. 10 of the 11 listeners rated NG [u:] as a better exemplar than NG [y:] of an AE back vowel ($p<0.02$ by a Sign test evaluated by the binomial expansion).[3] PF [u] was also rated as a better fit to AE back vowels than PF [y] for the three listeners who assimilated [y] to [u]; one listener who assimilated [y] to [i] rated it as a poorer exemplar than PF [i], and the remainder were inconsistent in their categorizations of one or both vowels, making goodness ratings difficult to interpret. In comparing ratings for NG [y:] with PF [y], 8 of the 9 listeners for whom a particular back AE vowel was the model response rated the NG vowel as a significantly better exemplar than PF [y] of that back vowel AE (Wilcoxon Signed-Ranks test, $N=9$, $T+=44$, $p<0.01$).

For NG [ø:, o:] and PF [ø, o], relative goodness ratings also reflected the judgment that front, rounded vowels were poorer exemplars of AE back vowels than were back, rounded vowels. All 11 participants rated NG [o:] as a better fit than NG [ø:] to some AE back vowel ($p<0.01$ by a Sign test); 10 of the 11 participants also rated PF [o:] as a better exemplar than PF [ø:] of some AE back vowel ($p<0.02$ by a Sign test). Because of the great variability within and across participants in the assimilation of NG [ʏ, œ] to various AE categories, an analysis of differences in goodness ratings was less interpretable.

2. Front, unrounded and low vowels

As Table II (columns 1–5) shows, both NG and PF front, unrounded vowels were perceptually assimilated primarily to their transcriptional counterparts in AE and considered very good exemplars of those categories. This reflects generally good consistency both within and across listeners in assimilation patterns. However, a few listeners were inconsistent in their perceptual assimilation of PF [e, ɛ] and one listener consistently assimilated PF [ɛ] to AE [eɪ]. The remaining eight listeners judged NG and PF [ɛ] to be equally good exemplars of AE [ɛ], despite large differences in F1 values (see Fig. 1). This can be contrasted with back NG [ʊ, ɔ] and PF [ɔ, o] (shown in Table I), which were not consistently assimilated to their AE counterparts.

As shown in Table II (columns 6–10), NG [ɑ:] was assimilated as a relatively good match to AE [ɑ:] by all but one listener. In contrast, NG and PF [a] were less consistently assimilated to AE vowels both within and across individual listeners. Again, most listeners' perceptual assimilation of the spectrally-similar NG [ɑ:/a] appeared not to reflect an influence of vowel duration on categorization patterns.

C. Discussion

These results generally replicated earlier research with respect to how front, rounded vowels in citation-form materials are perceptually assimilated by naïve AE listeners. They differed somewhat with respect to assimilation patterns for similar NG and PF vowels that vary phonetically from their AE transcriptional counterparts. In addition, patterns of assimilation of PF vowels, relative to NG vowels, could be evaluated for the same AE listeners.

Cross-language categorization patterns suggested that responses on NG [y:, ʏ, ø:] and PF [y, ø] were based primarily on context-independent relationships to AE phonological categories, i.e., their acoustic similarity to AE vowels produced in this context did not predict perceptual assimilation patterns. Rather, as predicted from previous research, these vowels were categorized as more similar to back than to front AE vowels. Only one participant assimilated PF [y] to AE [i], and none heard NG [y:] as more similar to an AE front vowel. In an earlier study with different NG speakers, but similar materials (Strange *et al.*, 2004), only 3 out of 12 AE listeners categorized NG [y:] as more similar to front than to back AE vowels. In the present study, NG [ʏ, ø:] and PF [ø] were also categorized as more similar to AE back vowels by all 11 listeners. In the earlier study, 2 out of 12 AE listeners assimilated these NG vowels to front AE categories.

A comparison of category goodness ratings indicated that almost all the listeners heard NG [y:, ø:] and PF [y, ø] as poorer exemplars of AE back vowel categories than NG [u:, o:] and PF [u, o]. This may be characterized as a category-goodness assimilation pattern for front vs back, rounded contrasts in the Perceptual Assimilation Model (PAM) framework (Best, 1995). Second, the finding of poorer within-listener consistency in categorization of the front, relative to the back, rounded NG and PF vowels also suggests that listeners detected phonetic differences between them. This might be interpreted as reflecting an uncategorized-categorized pattern according to PAM. Thus, in this study, listeners appeared to be able to access detailed phonetic information about the deviation of front, rounded NG and PF vowels from AE back vowels in this non-coronal context including, for most listeners, the perception that PF [y] was more deviant than NG [y] as an exemplar of any AE back vowel. The authors would expect then that in this context with these materials, discrimination of front/back rounded vowel contrasts would be significantly above chance for naïve AE listeners, although perhaps not as accurate as native listeners' performance.

NG [œ], which was acoustically similar to AE [ɛ], was nevertheless uncategorized for 8 of 11 AE listeners; these results replicate the results of Strange *et al.* (2004) for this vowel. With respect to the PAM taxonomy, NG [ɛ/œ] in this context was a category-goodness contrast for a minority of AE listeners, whereas for most, it was categorized-uncategorized. To our knowledge, this contrast has not been tested in studies of naïve AE listeners' perception of NG vowels.

The acoustic realization of NG [e:, o:] and PF [e, o] as somewhat higher on average than AE [eɪ, oʊ], as well as the fact that these NG and PF vowels are not diphthongized, led to the expectation that they would be perceived as more similar to higher AE vowels or as poor tokens of AE mid vowels. However, in an earlier study (Strange *et al.*, 2004), NG [o:] was consistently categorized as a relatively good exemplar of AE [oʊ], despite its acoustic dissimilarity, whereas 9 of the 12 listeners assimilated NG [e:] to AE [i:, ɪ]. The results of the present study did not replicate this finding. Here, NG [e:, o:] were both consistently categorized as their AE counterparts by most of the listeners. However, fewer listeners consistently categorized PF [e, o] as their AE counterparts, with more assimilation responses to higher AE vowels. These patterns of perceptual assimilation are only partially predictable from context-specific spectral similarity relationships (see the Appendix).

Listeners in the present study also categorized NG [ɛ] somewhat more consistently than PF [ɛ] to the AE counterpart; the NG results replicate the earlier finding for this vowel. In contrast, NG and PF [ɔ] were both poor perceptual matches to any AE vowel, even though NG [ɔ] was spectrally quite similar to its AE counterpart. This could be due to the fact that in NYE dialect, this vowel tends to be long and heavily diphthongized in some speakers' productions.[4] As in the earlier study, NG [ʊ] was not assimilated to its AE counterpart. However, although it was inconsistently categorized as a very poor exemplar of any AE vowel in the earlier study, here it was more consistently categorized as similar to AE [oʊ], as was predictable from the analysis of acoustic similarity. Finally, as in the earlier study, NG [ɪ] was consistently assimilated to its AE counterpart by most listeners.

On the basis of spectral and temporal similarities, differences in the assimilation of NG and PF low vowels were expected. However, assimilation patterns on NG [ɑ:, a] suggested that only a few listeners differentiated these vowels on the basis of their temporal and (small) spectral differences. For most listeners, this NG contrast constituted a single-category assimilation pattern according to the PAM (Best, 1995). Most listeners also categorized PF [a] as a good exemplar of AE [ɑ:], despite its short duration and greater spectral similarity to AE [æ:].

These data reveal patterns of perceptual similarity of NG and PF vowels to AE categories in citation-form utterances (non-coronal context). In the next study, the effects of contextual variation on assimilation patterns for vowels produced in sentence materials were explored. This allowed the authors to establish the extent to which listeners had access to context-specific phonetic information during online processing of continuous speech input.

III. STUDY 2: GERMAN AND FRENCH VOWELS IN SENTENCES

In an earlier acoustic study comparing NG, PF, and AE vowels in sentence materials, striking differences across languages in the contextual variation in coarticulated vowels were revealed (Strange *et al.*, 2007). For NG vowels in labial context, mid-syllable formant frequencies for all 14 vowels differed little from canonical values. In alveolar context, NG short vowels [a, ɔ, ʊ] showed some coarticulatory fronting and raising, but the remaining vowels changed little. In contrast, PF vowels in both contexts in sentence materials varied considerably from canonical values derived from citation-form utterances. In alveolar context especially, PF low and back vowels [a, ɔ, o, u] showed more coarticulatory raising and/or fronting than NG vowels, whereas front, unrounded vowels and [y] were slightly more back. Finally, AE vowels showed very small shifts from canonical values for all 11 vowels in labial context, but extreme fronting of high to mid back vowels [uː, ʊ, oː] and some raising and fronting of [ɛ, ʌ] in alveolar contexts.

Cross-language differences in coarticulatory patterns gave rise to notable differences in spectral similarity of NG and PF vowels to AE categories, as established by cross-language discriminant analyses of six speakers of each language (Strange *et al.*, 2007). NG and PF /y, ø/ were more similar to front AE vowels in labial context, whereas they were more similar to fronted allophones of back AE vowels in alveolar context, except for PF [y], which was still more similar to AE [i]. NG [ʏ, œ] were more similar to back rounded AE vowels in both contexts. Other NG and PF vowels also changed their spectral similarity to their AE transcriptional counterparts; NG [ɪ, eː, ɛ] and PF [ɛ] were somewhat better matches than in citation-form materials, while NG and PF [a] were spectrally more raised relative to their canonical targets and to AE low vowels.

Contextual variations in cross-language spectral and temporal similarity were predicted to affect perceptual assimilation patterns in the present study. It was also predicted that perceptual assimilation patterns might differ from those found in study 1 because here listeners were asked to judge cross-language similarity "on the fly" while listening to continuous speech utterances. A question of interest was the extent to which context-specific phonetic information was accessible to listeners as they made categorization responses and goodness judgments.

Using similar sentence materials, Strange *et al.* (2005) reported that naïve AE listeners did not differ systematically in overall categorization consistency or in median goodness ratings of NG front rounded vowels produced in labial, alveolar, and velar contexts; they were assimilated as fair exemplars of back AE vowels in all contexts. In that study, the context in which the vowels occurred varied randomly from trial to trial. In another study (Strange *et al.*, 2004) with NG vowels produced in [hVp] context in the same carrier sentence, all 12 AE listeners categorized NG front, rounded vowels (except for [œ]) as most similar to back AE categories, but judged them to be relatively poorer exemplars than NG back, rounded vowels. Thus, it is not clear whether it was the coarticulatory variability or the contextual uncertainty that led to the failure of listeners in Strange *et al.* (2005) to reflect context-specific differences in similarity of front and back, rounded NG vowels to AE vowels in their categorization and goodness ratings. In addition, whereas some similar NG vowels were assimilated differently in sentence and citation materials, there were few differences in assimilation patterns across labial, alveolar, and velar contexts in categorization consistency or judged goodness. It appears that listeners adopted a context-independent strategy for categorizing and rating the NG vowels when the immediate context varied from trial to trial and when the target syllables were embedded in sentence-length utterances.

Levy and Strange (2008) used a cross-speaker AXB discrimination task to examine naïve AE listeners on perceptual differentiation of front, rounded PF vowels. Stimuli were disyllables /raCVC/ in labial and alveolar contexts in phrase-length utterances, with contexts presented in separate blocks. The results supported the hypothesis that [y] was assimilated to a front AE vowel in labial context and to a back AE vowel in alveolar context by the majority of naïve listeners; [ø] was assimilated as a relatively poor exemplar of a back vowel in both contexts. However, no perceptual assimilation data were gathered on these listeners.

In follow-up experiments, Levy (2009) reported perceptual assimilation data for naïve and experienced L2 learners of French. The AE response alternatives included palatalized [ʲu] (as in "hue") and /ɝ/ (as in "herd"), as well as the other 11 vowel categories used in previous research (Strange *et al.*, 2004, 2005) and the present study. Perceptual assimilation patterns for naïve listeners showed significant differences as a function of context: PF [y] was judged more often as similar to [ʲu] in labial than in alveolar context, and there were more assimilations to AE [i] in labial context than in alveolar context. PF [ø][5] also differed with context for naïve listeners. The results suggest that both PF front and back, rounded vowels were perceived as similar to back AE [u] with the exception of PF /y/ in bilabial context.

In the present study, naïve AE listeners were tested on the complete (oral) vowel inventories of both NG and PF in a repeated measures design. Vowels produced in labial and alveolar contexts were presented in blocked format; order of context and of language was counterbalanced across listeners. Several questions were of interest.

(1) When listeners could anticipate the consonantal context, would assimilation of coarticulated NG and PF front, rounded vowels produced in labial and alveolar contexts reflect a context-specific mode of processing? If it did, we predicted the following.
   (a) Front, rounded NG and PF vowels (especially [y]) produced in labial context would be assimilated as poorer exemplars of AE back vowels than those produced in alveolar context.
   (b) PF [y] would be judged a poorer exemplar than NG [yː] of AE [uː] in labial context.

(2) Would judged goodness of NG and PF back, rounded vowels differ with context, given cross-language differences in their coarticulatory fronting? Specific predictions were the following.
   (a) NG [uː, oː] would be considered poorer exemplars of back AE categories in alveolar than in labial context because they were not fronted as much as their AE transcriptional counterparts.

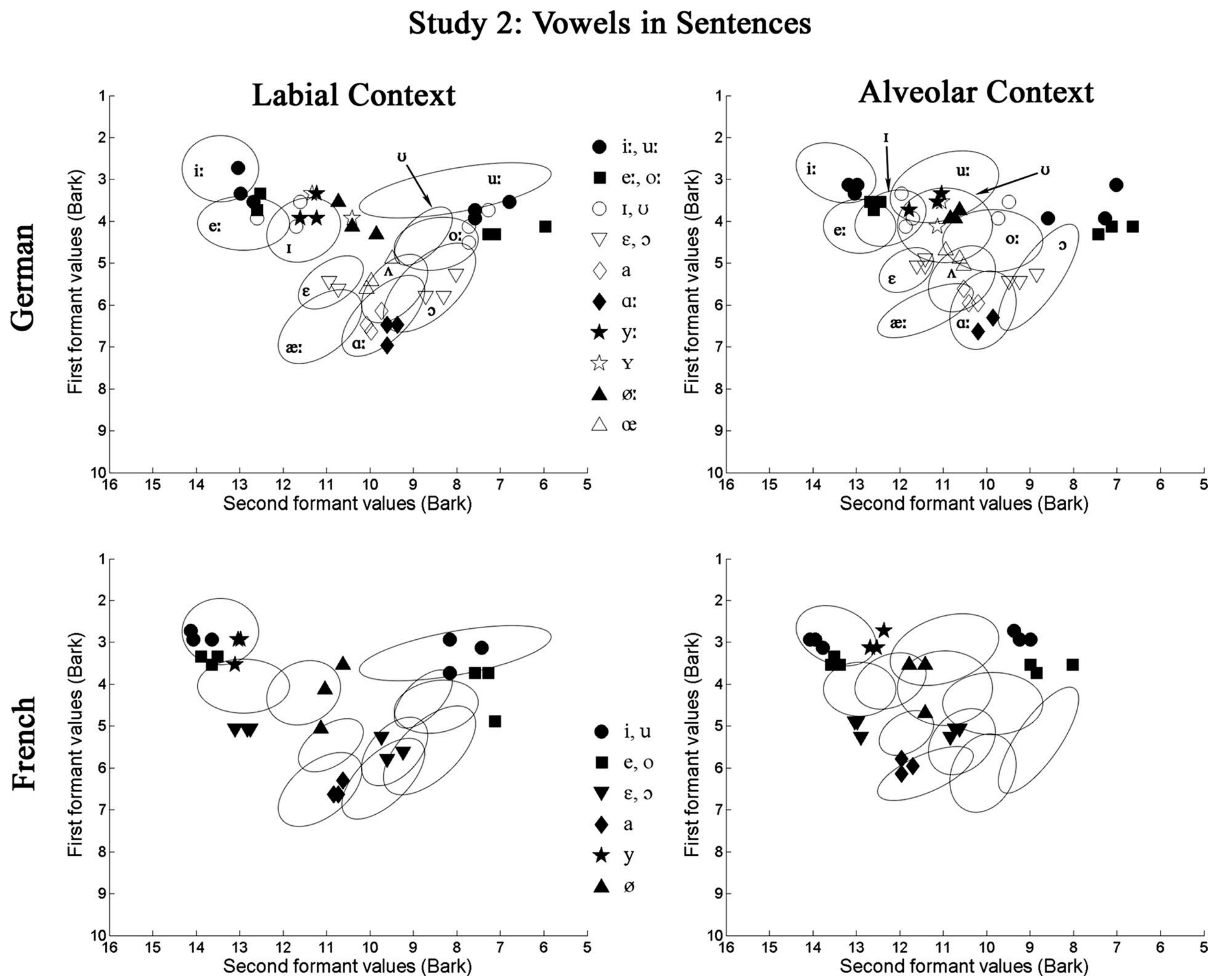

FIG. 2. NG (above) and PF (below) stimuli for study 2 (3 tokens of each vowel). Vowels were produced in labial context (left) and alveolar context (right) in nonce words embedded in sentences. Ellipses surround 11 AE vowels produced by 3 male speakers in the same sentence materials (labial context left, alveolar context right). For German vowels, short vowels are shown in open symbols, long vowels in closed symbols.

(b) PF back, rounded vowels would be considered better exemplars than NG back, rounded vowels of their AE counterparts in both contexts because they were more fronted and thus more similar to AE vowels.

(3) Would perceptual assimilation of low NG and PF vowels reflect relative differences in contextual raising across contexts? Specific predictions were the following.

(a) PF [a] would be assimilated more often than NG [a] to higher AE vowels, especially in labial context, where it was raised relative to canonical values.

(b) NG [a] would be assimilated more often to higher AE vowels in alveolar than in labial context because of its raising in alveolar context.

A. Method

1. Speakers and stimuli

The same two male native speakers of NG and PF as in study 1 produced the stimuli for study 2 (see Strange *et al.*, 2007). NG vowels were produced in the carrier sentence, "Ich habe fünf /gəCVCə/ gesagt;" PF vowels were produced in the carrier sentence, "J'ai dit neuf /ra/CVC/ à des amis." The target vowels occurred in the stressed or prominent syllable of the nonsense word; the consonantal contexts were bVp and dVt.[6] Recording procedures and stimulus selection were the same as in study 1; speakers produced the sentences fluently at a speaking rate that was appropriate for speaking to native listeners.

Figure 2 displays the stimuli in F1/F2 bark space, superimposed over the distributions of AE vowels produced by three males (Strange *et al.*, 2007) in labial and alveolar contexts in multisyllabic utterances embedded in a carrier sentence ("I said five gəCVCə this time"). To establish acoustic similarity patterns, context-specific linear discriminant analyses were performed in which the AE vowels produced in labial and alveolar contexts by the male AE speakers served as the training sets and the NG and PF stimulus materials served as the test sets. Two sets of analyses were conducted; one in which F1/F2/F3 bark values served as the input parameters for both training and test sets, and a second where vocalic duration was added as a fourth parameter. The Appendix presents the classification data for the first analyses of cross-language spectral similarities since the inclusion of duration had little effect on classification patterns, except for NG and PF [a] (more classifications as short [ʌ, ɛ], respectively).

There were clear differences in cross-language spectral similarity as a function of consonantal context as well as differences in acoustic similarity of the "same" NG and PF vowels to transcriptional counterparts in AE. Both NG and PF back, rounded vowels were, in general, more spectrally dissimilar from AE counterparts than in Study 1. In labial context, NG [oː, ɔ] were better spectral matches to AE counterparts than were PF [o, ɔ], whereas PF [u] was a better match than NG [u] to its AE counterpart. In alveolar context, the spectral dissimilarity of both NG and PF back, rounded vowels to AE counterparts was even greater because the AE high to mid back vowels in this context were produced as fronted allophones (see Fig. 2).

NG [yː, ʏ, øː]) were classified primarily as front AE vowels in labial context, whereas they were classified as back AE vowels when produced in alveolar context due to the extreme fronting of back AE vowels in this context. In contrast, PF front, rounded vowels were spectrally more similar to AE front vowels in both contexts (i.e., they were more front than NG vowels).

Front, unrounded NG vowels [iː, eː, ɪ, ɛ] were quite similar spectrally (and temporally) to their AE counterparts in both contexts, whereas PF [e, ɛ] were higher relative to AE (and NG) counterparts. Finally, while NG low vowels [ɑː, a] were both spectrally most similar to AE [ɑː], PF [a] was spectrally more similar to AE [æː] in both contexts. When vocalic duration was included as an input parameter, results indicated that NG and PF [a] and NG [ɔ] were more similar to AE [ʌ].

2. Procedures and tests

Testing procedures followed the same structure as in study 1, except that listeners heard two separate tests for each language: target vowels in labial context and in alveolar context. The orders of languages and contexts within languages were counterbalanced across participants. Prior to testing, listeners completed a familiarization test in which they heard AE vowels produced in sentences "I said five gaCVCa this time" with the vowel and consonantal context varying randomly. For this study, the key words were changed to "eek" [iː], "if" [ɪ], "ache" [eɪ], "heck" [ɛ], "as" [æː], "ah" [ɑː], "awe" [ɔ];, "uh" [ʌ], "hook" [ʊ], "oh" [oː], and "ooze"[uː] so that they contained no labial or alveolar stops. There were five familiarization blocks; feedback was given on blocks 1–4, but not on block 5. Listeners were required to make no more than 2 errors on block 5 (22 items) and no more than one error on any one vowel. Listeners then completed four tests of four blocks each for each context and each language. The first block of each test was for familiarization; data from the final three blocks (nine judgments/vowel/context) were retained for analysis. Subjects were tested in the same environment using the same equipment as in study 1.

3. Listeners

Participants were drawn from the same population of NYE speakers as in study 1. None had any experience with German or French or any other language with front, rounded vowels. A total of 28 participants was tested in the familiarization task. 11 failed to meet the criterion for further participation, and 1 who met the familiarization criterion failed to follow instructions in subsequent testing and was not included. Thus, 16 listeners completed all 4 experimental tests (4 male and 11 female); their average age was 31 years (range from 21 to 48 years). They all reported normal hearing.

B. Results

As in study 1, data on blocks 2–4 for all 16 participants on each NG and PF test were tallied, and categorization responses for each NG and PF vowel in each context were summed over the 16 listeners ($9\times16=144$ total trials for each vowel in each context and language). Overall modal responses and median goodness ratings on trials on which the modal response was selected were derived. In addition, the number of listeners who consistently (at least 7 out of 9 responses) categorized each NG and PF vowel as a particular AE vowel was tallied.

1. Back and front, rounded vowels

Given the differences across languages in the fronting of back, rounded vowels, it was expected that NG [uː, oː] might be heard as relatively poorer exemplars of their AE counterparts than in study 1. As Table III indicates, this proved true, especially in alveolar context; both group and individual data showed these vowels to be less consistently assimilated and with lower median goodness ratings than in study 1. NG [uː] was consistently assimilated to its AE counterpart by significantly fewer listeners in alveolar than in labial context [Fisher's Exact test, $p<0.04$). In contrast, PF [u] was a better fit to its AE counterpart in both contexts relative to study 1, although goodness ratings were slightly lower. PF [o] was less consistently categorized overall than PF [u] in labial context and fewer listeners consistently assimilated PF [o] than PF [u] to their AE counterparts (Fisher's Exact test, $p<0.01$, two-tailed test). Fewer individuals were consistent in assimilating PF [o] to its AE counterpart in labial than in alveolar context, but this difference was not statistically reliable.

NG [ʊ, ɔ] and PF [ɔ] showed very inconsistent patterns of assimilation both within and across listeners in both contexts. More listeners consistently categorized NG and PF [ɔ] as AE [ɔː] in alveolar than in labial context (Fisher's Exact tests, $p<0.06$; $p<0.04$, respectively), but approximately half the listeners were inconsistent in their categorization of this vowel in both contexts. Finally, NG [ʊ] was categorized inconsistently by all but one listener in labial context and all but three listeners in alveolar context, with responses distributed over all back AE vowels for the other participants. In general then, these mid-high and mid-low back, rounded NG and PF vowels can be considered uncategorized back vowels in both consonantal contexts for about half the AE listeners. This reflects, in part, their spectral differences from AE vowel distributions (Fig. 2) as well as differences in length and diphthongization from NYE dialect.

TABLE III. Perceptual assimilation of NG and PF back, rounded vowels to AE categories: Study 2—Sentence materials. Modal AE V is the AE vowel chosen most often, summing over all AE listeners. Percent is the overall percent of trials on which the modal response was chosen. (Rating) in the overall median goodness rating on modal response trials, summed over listeners. # of Ss is the number of AE listeners (out of 16) selecting a single response on at least 7 of 9 trials.

	Labial context					Alveolar context				
	NG V	Modal AE V	Categorization Percent	(Rating)	# of Ss	NG V	Modal AE V	Categorization Percent	(Rating)	# of Ss
(A)	uː	uː	86	(6)	15	uː	uː	67	(5)	9
	o:	oʊ	97	(7)	15	o:	oʊ	74	(7)	11 [oʊ], 3 [ɔː]
	ʊ	oʊ	47	(6.5)	1 [uː]	ʊ	ʊ	38	(5)	2 [ʊ], 1 [uː]
	ɔ	ʌ	30	(6)	2 [ɔː], 1 [oʊ], 1 [ʌ]	ɔ	ɔː	61	(6)	8 [ɔː]
	Labial context					Alveolar context				
	PF V	Modal AE V	Categorization Percent	(Rating)	# of Ss	PF V	Modal AE V	Categorization Percent	(Rating)	# of Ss
(B)	u	uː	94	(6)	16	u	uː	92	(6)	14
	o	oʊ	60	(6)	7 [oʊ], 3 [uː]	o	oʊ	71	(6)	10 [oʊ], 1 [uː], 1 [ɔː]
	ɔ	ʌ	38	(7)	4 [ʌ], 2 [oʊ], 1 [ɔː]	ɔ	oʊ	47	(5)	5 [ɔː], 4 [oʊ]

NG front, rounded vowels in both labial and alveolar contexts (Table IV) were assimilated more often to back than to front AE categories, although the overall consistency with which they were assimilated to particular AE back vowels differed considerably across particular NG vowels. PF front, rounded vowels were also assimilated primarily to AE back vowels in both contexts, although overall consistency varied by context for [y] and the group modal AE vowel categories differed across contexts for [ø].

NG [y:] and PF [y] were assimilated primarily to AE [u:] in labial context. Whereas the group overall consistency and median goodness ratings suggested that PF [y] was heard as less similar than NG [y:], this was due primarily to two listeners who assimilated PF [y] consistently to AE [i:]. For the remaining listeners, there was no significant difference in number of listeners who consistently categorized each vowel as AE [u:](13 vs 11), nor in goodness ratings across the two languages (Wilcoxon Signed-Ranks test, $N=10$, $T+=38$, n.s.). In alveolar context, both NG [y:] and PF [y] were assimilated overwhelmingly to AE [u:]; only three participants were inconsistent in categorizing either NG [y:] or PF [y]. For the other 13 listeners, only 5 rated the NG [y:] as a better exemplar than the PF [y] of AE [u:] (Wilcoxon Signed-Ranks test, $N=13$, $T+=54.5$, n.s.). Thus, in both contexts, NG [y:] and PF [y] were assimilated as relatively good exemplars of AE [u:] by most naïve AE listeners. Indeed, these vowels

TABLE IV. Perceptual assimilation of NG and PF front, rounded vowels to AE categories: Study 2—Sentence materials. Modal AE V is the AE vowel chosen most often, summing over all AE listeners. Percent is the overall percent of trials on which the modal response was chosen. (Rating) is the overall median goodness rating on modal response trials, summed over listeners. # of Ss is the number of AE listeners (out of 16) selecting a single response on at least 7 of 9 trials.

	Labial context					Alveolar context				
	NG V	Modal AE V	Categorization Percent	(Rating)	# of Ss	NG V	Modal AE V	Categorization Percent	(Rating)	# of Ss
(A)	yː	uː	83	(6)	13	yː	uː	92	(6)	15
	øː	uː	31	(5)	2 [uː], 2 [ʌ] 1 [ʊ]	øː	ʊ	30	(3)	2 [ʊ], 2 [uː] 1[ʌ], 1[oʊ]
	ʏ	uː	44	(5)	3	ʏ	uː	52	(6)	4 [uː], 2 [ʊ]
	œ	ʌ	75	(6)	9	œ	ʌ	69	(6)	8 [ʌ], 1 [ʊ] 1[oʊ]
	Labial context					Alveolar context				
	PF V	Modal AE V	Categorization Percent	(Rating)	# of Ss	PF V	Modal AE V	Categorization Percent	(Rating)	# of Ss
(B)	y	uː	74	(4)	11 [uː], 2 [i:]	y	uː	94	(6)	14
	ø	ʌ	38	(4)	3 [ʌ], 1 [uː] 1 [ʊ]	ø	oʊ	44	(4)	3 [oʊ], 1 [uː]

TABLE V. Perceptual assimilation of NG and PF front, unrounded and low vowels to AE categories: Study 2—Sentence materials. Modal AE V is the AE vowel chosen most often, summing over all AE listeners. Percent is the overall percent of trials on which the modal response was chosen. (Rating) is the overall median goodness rating on modal response trials, summed over listeners. # of Ss is the number of AE listeners (out of 16) selecting a single response on at least 7 of 9 trials.

	Labial context					Alveolar context				
	NG V	Modal AE V	Categorization Percent	(Rating)	# of Ss	NG V	Modal AE V	Categorization Percent	(Rating)	# of Ss
(A)	iː	iː	100	(8)	16	iː	iː	100	(7)	16
	eː	eɪ	71	(7)	10 [eɪ], 3 [iː]	eː	eɪ	87	(7)	14
	ɪ	ɪ	75	(7)	9	ɪ	ɪ	94	(7)	15
	ε	ε	99	(7)	16	ε	ε	94	(7)	14
	ɑː	ɑː	84	(7)	13	ɑː	ɑː	88	(7)	12
	a	ɑː	84	(7)	12	a	ʌ	74	(6)	8 [ʌ], 1 [ɑː]
	Labial context					Alveolar context				
	PF V	Modal AE V	Categorization Percent	(Rating)	# of Ss	PF V	Modal AE V	Categorization Percent	(Rating)	# of Ss
(B)	i	iː	97	(7)	16	i	iː	90	(7)	13
	e	eɪ	51	(6)	6 [eɪ], 1 [iː], 1 [ɪ]	e	eɪ	40	(6)	2 [ɪ], 1 [iː]
	ε	ε	79	(6)	12	ε	ε	85	(6)	13
	a	ɑː	64	(6)	7 [ɑː], 2 [ʌ], 1 [ε]	a	ɑː	49	(7)	7 [ɑː], 3 [ε], 2 [eɪ], 1 [æː]

were considered good or better exemplars of AE [uː] than were NG and PF /u/ except for PF [y] in labial context (see Table IV).

In contrast, NG [øː] and PF [ø] were not assimilated to any one AE vowel on a majority of trials in either context, reflecting both within- and across-listener inconsistencies. Thus, NG [øː] and PF [ø] can be considered uncategorizable back vowels for naïve AE listeners when produced in sentence materials. NG [ʏ] was also uncategorizable in both contexts for most listeners. The majority of listeners were consistent in their categorization of NG [œ] as AE [ʌ] in one or the other context, but only six listeners were consistent in both contexts. For the remaining listeners, this vowel was also uncategorizable in one or both contexts.

2. Front, unrounded, and low vowels

As seen in Table V, NG [iː] and PF [i] were very consistently categorized as their AE transcriptional counterpart in both contexts. NG and PF [ε] were only slightly less consistently assimilated to their AE transcriptional counterpart in both contexts. NG [eː, ɪ] and PF [e] showed different group and individual patterns of assimilation across languages and contexts. In labial context, NG [eː] was more consistently categorized than PF [e] as AE [eɪ] overall, but this was not reliable for individual subjects (Fisher's Exact test, n.s.). However, for the ten listeners whose modal response was AE [eɪ] for both NG [eː] and PF [e], goodness ratings were significantly higher for the NG vowel (Wilcoxon Signed-Ranks test, $N=8$, $T+=32.5$, $p<0.03$). In alveolar context, PF [e] was not consistently assimilated to AE [eɪ] by any listener, whereas 14 listeners consistently heard the NG [eː] as a relatively good exemplar of AE [eː] (Fisher's exact test, $p<0.001$). NG [ɪ] was consistently assimilated to AE [ɪ] by more listeners in alveolar than in labial context (Fisher's Exact test, $p<0.04$), reflecting their acoustic differences (see Appendix, Table VI).

For the three low vowels, NG [ɑː, a] and PF [a], the group modal assimilation responses were AE [ɑː], except for NG [a] in alveolar context, which was assimilated primarily to AE [ʌ]. However, analysis of individual listeners' response patterns revealed differences across contexts and languages. NG [a] was consistently categorized by significantly more listeners as AE [ɑː] in labial than in alveolar context (12 vs 1, Fisher's Exact test, $p<0.001$). In labial context, ten listeners assimilated both NG [ɑː, a] to the same AE category with identical or very similar goodness ratings, whereas in alveolar context, only one listener assimilated both vowels as equally good exemplars of AE [ɑː] (Fisher's Exact test, $p<0.01$). Eight listeners assimilated them consistently to AE [ɑː] and [ʌ], respectively. This reflects the fact that NG [a] is fronted and raised in alveolar context (Strange *et al.*, 2007). For other listeners, this contrast constituted a categorized-uncategorized contrast in both contexts.

For PF [a], the overall modal assimilation to AE [ɑː] was lower than for NG [a] in both contexts primarily due to across-listener variability. In labial context, 10 listeners were consistent in categorization responses, but selected different AE vowels; 13 listeners consistently categorized PF [a] as a particular AE vowel in alveolar context. However, only six listeners assimilated PF [a] in the same pattern across labial and alveolar contexts. Note that only one listener perceived PF [a] as most similar to AE [æː] in alveolar context.

C. Discussion

These results demonstrated differences across languages and contexts in naïve AE listeners' perceptual assimilation of vowels in sentence materials. In some cases, these patterns of perceived similarity could not be predicted from context-specific, cross-language spectral similarity patterns (see the Appendix). In other cases, differences in perceptual similarity patterns were predicted from changes in acoustic similarities across contexts and languages due to cross-language differences in coarticulatory patterns (Strange *et al.*, 2007).

NG and PF front, rounded vowels were assimilated to back AE vowels even when they were spectrally more similar to front AE vowels. Almost all listeners assimilated NG [y:] as a relatively good exemplar of AE [u:] in both consonantal contexts. Two listeners consistently assimilated PF [y] to AE [i:] in labial context, but the remaining listeners assimilated PF [y] to AE [u:], with no significant differences in goodness ratings across NG [y:] and PF [y] in this context. In alveolar context, all listeners heard PF [y] as very similar to fronted allophones of AE [u:]. The remaining front, rounded vowels were, in general, not consistently categorized within or across listeners as any particular back AE vowel in both contexts.

The results for NG front, rounded vowels by and large replicate those reported in Strange *et al.* (2005), for which both NG speakers and the AE dialect group (mostly Midwestern-born living in Florida) differed from the present study. In general, when sentence materials are used, naïve AE listeners perceive front vs back, rounded NG pairs, especially [y:/u:], as very similar to each other and more similar to back than to front AE vowels in both coronal and non-coronal contexts. The results for the PF front, rounded vowels are less easily compared with those reported by Levy (2009) because the latter study included the AE palatalized [ʲu] response category. However, as a group, naïve AE listeners in that study assimilated PF [y] in labial context to AE [i:] on a small proportion of trials and the proportion of [ʲu] responses was greater for PF [y] in labial than in alveolar context. Thus, listeners heard PF [y] as less similar to AE [u] in labial than in alveolar context. Levy also reported less consistency in individuals' assimilation patterns for PF [ø] than for PF [y] in labial context. In alveolar context, the two PF vowels were assimilated with the same overall consistency. Thus, Levy (2009) concluded that naïve AE listeners' responses to PF front, rounded vowels produced in sentence materials showed some context-specific patterns of assimilation. In the present study, there was less evidence that listeners heard the extremely front PF [y] as a poorer exemplar of AE [u] in labial than in alveolar context.

Assimilation patterns for back, rounded NG and PF vowels showed that AE listeners were able to access some context-specific phonetic information about cross-language differences in coarticulatory variation for these similar NG and PF vowels. NG [u:] in alveolar context, which was acoustically farthest back (lowest F2 values), was judged a poorer exemplar of the fronted allophone of AE [u:] appropriate in that context. Group data appeared to show that NG [o:] and PF [o] were assimilated to AE [oʊ] somewhat differently across contexts, although the differences were not reliable across individual listeners' data. PF [o] was assimilated to other AE back vowels or uncaegorizable by many listeners.

Perceptual similarity patterns with respect to vowel height contrasts in front, unrounded and back, rounded vowels for these sentence materials differed from those reported in study 1 and showed marked effects due to consonantal context. NG [o:] was heard as very similar to AE [oʊ] in labial context; when coarticulated with alveolar consonants it was categorized as AE [ɔ:] or as in between [o:] and [ɔ:] by many listeners. In contrast, NG [e:] was perceptually more similar to its AE counterpart in alveolar than in labial context. The latter results were not predictable from the spectral similarity patterns derived from discriminant analysis. In general, PF [o, e, ɛ] were perceived as poorer exemplars than the same NG vowels of their AE counterparts in both contexts. This was predictable from their relatively higher locations (lower F1 values) in vowel space than for the NG vowels. The authors would predict therefore that the PF [e/ɛ] contrast would be more difficult to discriminate[7] (cf., Gottfried, 1984) than the same contrast in NG. They are not aware of any studies that examine the perception of this contrast by AE learners of German. Likewise, PF [o/ɔ] might be expected to be more difficult than the same contrast in NG [see Gottfried and Beddor (1988) for French data]. For both contrasts, if AE learners of German could be trained to attend to duration differences, they should be able to distinguish these vowels easily; in French, duration differences are more subtle or nonexistent (Strange *et al.*, 2007).

Patterns of perceptual assimilation of NG [ɑ:, a] and PF [a] showed that AE listeners varied their responses as a function of differences in the phonetic realization of these low vowels across languages and contexts. In labial context, NG [ɑ:, a] were both assimilated AE [ɑ:]; in alveolar context, short NG [a] was raised and fronted enough that most AE listeners perceived it as more similar to AE [ʌ]. AE listeners also assimilated PF [a] differently in labial and alveolar contexts; however, these differences could not be predicted readily from spectral or temporal similarity patterns. In general, PF [a] was a poor perceptual match to any AE low vowel. Because PF includes only one (oral) low vowel, AE learners of French would not be predicted to have difficulty discriminating this vowel from PF [ɛ, ɔ], which are quite high phonetically (low F1 values) relative to [a]. However, based on individual differences in perceptual assimilation patterns, the authors might expect considerable problems in accurate *production* of PF [a] in some contexts.

More generally, a significant finding of the present study was that perceptual assimilation of NG and PF vowels presented in coarticulated nonsense words embedded in carrier sentences often differed from the patterns of assimilation revealed in study 1, in which the vowels were produced and presented in citation-form utterances. These differences are discussed in Sec. IV.

IV. GENERAL DISCUSSION

The data from both studies are summarized here and implications for current models of non-native and L2 speech perception are discussed. In Sec. IV A, the authors characterize perceptual assimilation patterns for German and French front, rounded vowels, which would be considered "new" vowels in Flege's SLM framework (Flege, 1995; Flege and Hillenbrand, 1984). From comparisons of perceptual similarity of front vs back, rounded vowels, the authors draw conclusions about how these contrasts differ across languages, speaking styles, and phonetic contexts with respect to Best's PAM taxonomy of assimilation patterns (Best, 1995; Best and Tyler, 2007). In Sec. IV B, they characterize perceptual assimilation patterns of other German and French vowels that have transcriptional counterparts in English. These might be considered similar vowels in the SLM framework. Again, differences in assimilation patterns as a function of language, stimulus materials, and phonetic context are characterized.

A. Front vs back, rounded vowels

In replication of earlier cross-language categorization studies of French (Levy, 2009) and German (Polka, 1995; Strange *et al.*, 2004, 2005), front, rounded vowels were generally perceived by naïve AE listeners as more similar to back than to front AE vowels in both citation and sentence materials. As expected, NG and PF back, rounded vowels were also assimilated to back AE categories in all contexts, although goodness ratings varied considerably across particular vowels, languages, citation vs sentence materials, and consonantal contexts.

In study 1, NG and PF back, rounded vowels were generally heard as much better exemplars of AE back vowels than were NG and PF front, rounded vowels. Second, the majority of AE listeners were less consistent in their categorization responses of NG [ʏ, øː, œ] and PF [y, ø] to particular AE back vowels, suggesting that these vowels were heard as Uncategorizable back vowels in citation-form utterances. Thus, contrasts between front vs back, rounded vowels in NG and PF demonstrated category goodness or uncategorized-categorized patterns of perceptual assimilation for the majority of naïve AE listeners, predictive of intermediate levels of discrimination difficulty (Best, 1995). In study 2, listeners' perceptual assimilation patterns suggested that detailed, context-specific phonetic information was less accessible to listeners when they categorized and judged the goodness of these new vowels. NG [uː/yː] and PF [u/y] were judged as equally good exemplars of AE [uː] by the majority of listeners, especially when the vowels were surrounded by alveolar consonants, despite large differences in acoustic structure (i.e., differences in F2 > 3 barks). Thus, in sentence materials, these contrasts were assimilated in single category or category goodness patterns with very small goodness differences by most listeners. In contrast, NG [oː/øː] and PF [o/ø] reflected, for the most part, categorized-uncategorized patterns, as they did in study 1.

The results of these two studies suggest that perceptual assimilation patterns derived from studies using citation materials (e.g., Polka, 1995; Best *et al.*, 1996; study 1 here) may significantly underestimate discrimination difficulties involving some NG and PF front, rounded vowels for beginning AE L2 learners in online speech processing situations. This may be especially true for the high vowels, where front vs back, rounded vowels constitute allophonic variations in AE [uː]. Furthermore, AE listeners appeared not to attend to duration differences in categorizing and rating NG [øː/ʏ]. Context-specific spectral similarity relationships did not predict perceptual assimilation patterns for front, rounded vowels in either language. Thus, the authors conclude that, under stimulus and task conditions approaching continuous speech processing, attunement to language-general, acoustic-phonetic L1/L2 dissimilarities is not possible for most naïve listeners when judging vowels that do not occur as distinct phonological categories in their L1. Rather, naïve listeners must use L1 SPRs (Strange and Shafer, 2008) to categorize these non-native vowel segments. Even when the immediate phonetic context is not changing, listeners seem unable to make consistent judgments about the phonetic appropriateness of new vowels in those contexts. That is, they appear to use an L1 phonological mode of perception and fail to differentiate distinctive L2 vowels that are allophonic variants in L1, despite very large differences in their spectral structure.

B. Height contrasts and low vowels

Almost all listeners heard dissimilarities among NG [iː, eː, ɛ] and among PF [i, e, ɛ] in both studies 1 and 2, despite differences from AE counterparts in relative height of the mid and mid-low vowels in some or all contexts. Thus, predictions based on context-specific spectral similarity patterns that PF [ɛ] would be perceived as similar to AE [eɪ] or [ɪ] and that [e/i, e/ɛ] would yield single category assimilation patterns (cf. Gottfried, 1984) were not borne out for most AE listeners in this study. Similarly, the mid to mid-low, back vowel pairs in both languages were generally perceived as dissimilar by most AE listeners, except for PF [ɔ/o] in alveolar context (see Gottfried and Beddor, 1988). Again, these patterns were, in general, not predictable on the basis of spectral similarity relationships with AE vowels (see Figs. 1 and 2). Perceptual assimilation patterns in study 2 for these vowels were more similar to those in study 1 than were contrasts involving the front, rounded vowels. In general, pairs of similar vowels in both NG and PF that differed in height (as well as length and/or diphthongization) from their AE counterparts showed two-category or categorized-uncategorized patterns. This suggests that AE listeners were attuned to small height differences (F1 values), as would be expected given that AE contrasts five vowel heights. Thus, even though these vowels (except NG [ɛ]) differed from their AE counterparts in relative locations in vowel space, AE listeners were apparently able to differentiate them after they had a bit of practice with each speaker's complete vowel inventory (i.e., block 1 of the tests in which all three tokens of each vowel were presented once). That is, they appeared to be able to adjust their perceptual boundaries for similar vowels rather rapidly within the context of the experiment. Such rapid adjustment is useful in adapting to accented versions of English spoken by native speakers (Bradlow and Bent, 2008).

Finally, perceptual assimilation patterns for NG [ɑː/a] and PF [a] indicate that these vowels were perceived as similar to AE [ɑː] by more listeners in non-coronal contexts (study 1 and labial condition of study 2) than in coronal consonants (study 2, alveolar condition). The greater differentiation in alveolar context reflects the fact that NG and PF [a] are raised (and more spectrally distant from NG [ɑː]) in this context. In both studies 1 and 2, most AE listeners' performance indicated that the large duration differences between the NG vowels did not affect perceptual assimilation patterns. Thus, NG [ɑː/a]) might be difficult for most AE L2 learners of German to discriminate especially in non-coronal contexts where they overlap almost completely in formant structure, unless the learners have been explicitly taught to attend to duration differences.

To conclude, similarities and differences in the patterns of perceptual assimilation of non-native vowels by naïve listeners across languages, prosodic contexts, and consonantal contexts lead to the following generalizations:

(1) Perceptual assimilation tests of non-native vowels that have no phonologically distinctive counterparts in the native language (new vowels) often show different patterns of perceived L1/L2 similarity from those predicted from context-specific comparisons of their spectral and temporal properties. Patterns of assimilation are better predicted on the basis of cross-language differences in the systematic allophonic characteristics of vowel categories across languages. In the case demonstrated here, the authors conclude that front, rounded vowels are assimilated to AE back vowels because AE back vowels include highly fronted allophones. That is, that portion of "vowel space" occupied by (contrastive) front, rounded vowels in NG and PF has been subsumed by phonologically back, rounded vowels in AE.

(2) Direct tests of perceptual similarity may be the best predictors of discrimination problems by L2 learners if details about systematic allophonic variations in native and non-native phonological categories are unknown. However, perceptual assimilation tests using citation-form utterances may not accurately predict beginning L2 listeners' discrimination difficulties when listening to continuous speech utterances. Thus, to be maximally generalizable, tests of cross-language similarity of vowels might better be performed using materials in which vowels are produced in multiple consonantal contexts in phrase-length utterances. In addition, individual listeners often show markedly different patterns of perceived similarity; thus, it would be valuable to examine individual L2 learners' perceptual similarity patterns in order to make better predictions about their learning difficulties and to structure individualized training materials for them.

(3) Variations in perceptual assimilation patterns across languages, contexts, and prosodic conditions allow the authors to infer that listeners' knowledge of native categories includes both language-specific phonetic detail related to systematic allophonic variation and context-independent similarity relationships, traditionally characterized by a phonemic level of linguistic analysis. In the automatic selective perception model (Strange and Shafer, 2008), it is hypothesized that there are two "modes" of perception—a phonetic mode and a phonological mode. Perceptual responses may reflect either or both modes, depending upon experimental variables such as stimulus complexity and task demands (cf., Werker and Curtin, 2005).

(4) In perceptual assimilation tests using phrase-length materials, naïve listeners may not have access to detailed phonetic information when categorizing new non-native vowels. However, they do appear to be attuned to small phonetic differences in the phonetic realization of similar non-native vowels. The authors infer that L1 SPRs for perceiving native phonological categories are subject to rapid and temporary readjustment, as when native listeners are listening to non-native speakers' utterances.

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APPENDIX

See Table VI.

TABLE VI. Context-specific discriminant analyses of NG and PF vowels tested against AE categories (F1, F2, and F3 in barks).

	German vowels		
	hVbə	gəbVpə	gədVtə
iː	i 2, e 1	i 2, e 1	i 3
eː	e 3	e 3	e 2, ɪ 1
ɪ	ɪ 3	ɪ 2, e 1	ɪ 3
ɛ	ɛ 3	ɛ 3	ɛ 3
yː	ɪ 3	ɪ 3	u 3
øː	ɪ 3	ɪ 2, ʊ 1	u 2, ʊ 1
ʏ	ɪ 2, ʊ 1	ɪ 3	ʊ 1, u 1, ɪ 1
œ	ɛ 3	ʌ 1, o 1, ɛ 1	ʌ 2, ɛ 1
uː	u 2, o 1	o 3	ɔ 2, o1
oː	o 3	o 3	ɔ 3
ʊ	o 3	o 3	o 3
ɔ	ɔ 3	ɔ 2, ɑ 1	ɔ 2, o1
ɑː	ɑ 3	ɑ 3	ɑ 3
a	ʌ 2, ɑ 1	ɑ 3	ɑ 2, ʌ 1
	French vowels		
	Vb(ə)	rab Vp(ə)	radVt(ə)
i	i 3	i 3	i 3
e	i 2, e 1	i 3	i 3
ɛ	e 3	ɪ 2, e 1	e 2, ɛ 1
y	e 3	i 2, e 1	i 3
ø	ɪ 3	ɪ 2, ɛ 1	ɪ 2, ɛ 1
u	u 3	u 3	o 3
o	o 3	u 2, ɔ 1	ɔ 2, o 1
ɔ	ʌ 2, ʊ 1	ʌ 2, ʊ 1	ʌ 3
a	æ 3	æ 3	æ 3

[1]Medians were used as the measure of central tendency because the authors assumed that goodness ratings constituted only an ordinal level of measurement (see Strange, 2007a).

[2]This minimal criterion requires that each token of a vowel category must be categorized as the same AE vowel at least once (3 tokens × 3 repetitions). In many cases, all three vowels were categorized as the same AE vowel on all repetitions.

[3]Nonparametric statistics (Sign tests and Wilcoxon Signed-Ranks tests) are the appropriate statistics for repeated measures comparisons of ordinal data.

[4]In Strange *et al.* (2004), most AE listeners were not from the Northeast, and some did not differentiate [ɑː/ɔː] in their own speech.

[5]Levy and Strange (2008) and Levy (2009) used [œ] to represent the mid, front, rounded PF vowel represented here as [ø]. PF [œ] and [ø] are typically considered allophones in French.

[6]None of the NG and PF nonsense utterances were lexical items in English. Thus, lexical effects that could have confounded earlier results using CVC utterances were minimized here.

[7]The /e, ɛ/ contrast is phonemically contrastive in French for many lexical pairs and, in some dialects, signifies a grammatical marker, differentiating the conditional and future tenses (first person, singular). Failure of AE listeners to discriminate these French vowels may thus lead to difficulty in perceiving the correct tense of a verb.

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