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Testing a place-of-articulation double phoneme boundary in English-Tamil bilinguals

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Abstract. Categorical perception work in bilinguals has been found to support a Dual Language System Hypothesis, which states that bilinguals use one of two language-specific phonemic boundaries dependent on language context. This phenomenon of the double phoneme boundary has only been tested on the Voice Onset Time continuum. The current study tests bilingual speakers for a double phoneme boundary along the place-of-articulation (POA) continuum. English contrasts between dental and alveolar POAs whereas Indian Tamil contrasts between dental and retroflex POAs. In this study, American English-Indian Tamil bilinguals performed an Identification Task and a Discrimination Task in an English language session and a Tamil language session to demonstrate if they would place a dental category boundary at different points along a stimulus continuum between sessions. Participants did not demonstrate a shift in boundary location and a double phoneme boundary. Participants instead demonstrated two boundaries and thus a three-way categorization in both language contexts for POA, supporting a Unitary Language System. Further studies testing English and Tamil monolinguals would clarify if there is truly a unique bilingual categorization mechanism, or if bilinguals and monolinguals can both be explained via the Perceptual Assimilation Model.

Keywords. place-of-articulation, bilingualism, double phoneme boundary, categorical perception, categorical boundary, Tamil

1. Introduction. Languages use unique phonemic inventories. Speakers of a given language categorize continuous phonetic stimuli into the relevant phonemes. Monolingual categorical perception is fairly well-understood, whereas bilingual categorical perception may use one of a number of approaches. Bilingual speakers may develop and use two monolingual-like phonemic representations, or they may retain all of their phonemic categories at all times. Recent studies have demonstrated bilinguals' use of two phonemic inventories in respective language contexts, however the majority have focused on Voice Onset Time (VOT) contrasts. The goal of the present study is to examine the potential dual phonemic inventories in bilinguals along a place-of-articulation (POA) continuum, of which perception may be complicated by the use of multiple acoustic cues.

1.1. MONOLINGUAL SPEECH PERCEPTION. Speakers perceive continuous speech sounds through categories relevant to their language. Liberman et al. (1957) showed how monolingual English speakers categorize synthetic speech sounds ranging in POA from /b/ to /d/ to /g/. Speakers were more adept at discriminating between stimuli that straddled a categorical boundary between phonemes than stimuli that fell within a phoneme category (a Discrimination paradigm). Speakers also showed sharp inflections when identifying (labeling) the stimuli as one of the given phonemes (an Identification paradigm). Phoneme boundaries are known to be language-specific. For example, Lisker and Abramson (1970) found that monolingual English speakers displayed a

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single VOT boundary at +25 milliseconds, whereas monolingual Thai speakers displayed a VOT boundary at -20 milliseconds and another at +40 milliseconds. However, these category boundaries are learned features. Trehub (1976) found that infants under 4 months of age could discriminate contrasts that were native to their home language of English, as well as contrasts that were "nonnative" (not present in their home language) such as oral versus nasal vowels and strident versus non-strident consonants. Monolingual English adults, however, were only able to discriminate English contrasts and not nonnative contrasts. Thus, it must be that children learn their language's contrastive boundaries through use over time.

Monolinguals' boundaries between phonemic categories have been shown to "shift" when sufficiently primed. Cooper (1974) administered Identification and Discrimination paradigms on monolingual English speakers using a POA continuum. Participants were tested once unprimed, and then retested following presentation of a certain POA stimulus. Participants placed category boundaries at significantly different stimuli along the continuum following priming, indicating a shift in the boundary. This is believed to be due to the Perceptual Assimilation Model (PAM) proposed by Best (1994). PAM predicts that monolingual listeners map nonnative sounds onto their closest native phonemic category if they are gesturally similar. As a result, nonnative contrasts between phones that can be mapped onto similar native phones can be discriminated, and the nonnative boundary displayed in this test is located elsewhere than the native boundary. Thus, the monolingual category boundary shifts in response to nonnative contexts.

1.2. MULTILINGUAL PHONEMIC REPRESENTATIONS. As reviewed in Genesee (1989), initial studies (Redlinger and Park 1980; Volterra and Taeschner 1978; Swain 1972; Swain 1977) of bilingual speakers' language systems had determined from child language-switching practices that bilingual children began with a single language system which did not discriminate between their two languages. During the course of child development, this initial Unitary Language System (ULS) would eventually develop into a Dual Language System (DLS) where the child would store their two languages separately. Genesee (1989) refutes the interpretations of these initial studies, arguing that adult bilinguals' use of language-switching sufficiently mirrors child evidence of language-switching, and thus children must also use the DLS present in adults. The DLS Hypothesis states that adult bilinguals maintain two discrete phonemic inventories, and thus two sets of phonemic category boundaries, each used separately in the bilingual speakers' two language modes. The presence of a ULS in bilingual adults has not been considered. Bilingualism literature has to date focused on evidence for the DLS Hypothesis.

While many studies have confirmed the locations of monolingual phonemic boundaries, fewer have considered how bilingual and multilingual speakers perceive category boundaries, which are different between their respective languages. Caramazza et al. (1973) attempted to demonstrate that bilinguals' phonemic representations in their two languages would match those of monolingual speakers, supporting a DLS. However, results showed phonemic boundaries intermediate to the monolinguals'. Elman et al. (1977) believed that the experimental paradigm used in Caramazza et al. (1973) had not sufficiently primed speakers to use each of their two languages' phonemic inventories and aimed to induce clearer language modes by conducting the entire experimental procedure in the target language. Elman et al. (1977) tested where Spanish-English bilinguals placed phoneme boundary locations given English and Spanish language contexts. Specifically, monolingual English speakers, monolingual Spanish speakers, and bilingual Spanish-English speakers performed a Discrimination Task and an Identification Task for bilabial plosive stimuli varying along a VOT continuum. The bilingual Spanish-English speakers performed the tasks in both language contexts. The results showed that bilingual speakers categorized the same stimuli differently when presented in the Spanish-language versus the English-language context, with an earlier boundary in the English context and later boundary in the Spanish context. The difference in boundary location is referred to as a "boundary shift" between languages. This study proposed that "higher-order linguistic information," such as an induced language mode primed by the language context, rather than only acoustic information, influences phoneme recognition.

Elman et al. (1977) did not test monolingual speakers in both language contexts, and thus it lacked a true control to compare to bilingual performance. In response, Bohn and Flege (1993) tested both bilinguals and monolinguals in two language contexts. Comparing responses in an Identification Task, bilinguals performed as expected with significantly different label proportions between contexts. However, monolinguals also responded with significantly different label proportions. Similar results were found in Garcia-Sierra et al. (2009), which named the bilingual shift in boundary position the "double phoneme boundary". These results don't appear to support the DLS Hypothesis that bilinguals are uniquely able to switch language mode and monolinguals are not. Instead, PAM is able to explain that monolinguals display a boundary shift in response to language context influence because they assimilate to nonnative contrasts. This also explains bilinguals' performance, and thus is a more robust solution.

The aforementioned studies of the double phoneme boundary only focus on categorical perception along a continuum of VOT. Few studies have examined the POA continuum, which notably varies by multiple acoustic cues rather than just one. Stop consonants in particular are discriminated by their burst frequencies and formant transitions of F2 and F3 (Syrdal 1983). In one study of the bilingual POA continuum, Sundara and Polka (2008), rather than synthesizing unique stimuli along a continuum as did Liberman et al. (1957), used natural recordings of French or English speakers producing either dental or alveolar stop consonants. This study found that adult simultaneous Canadian French-Canadian English bilinguals, who could access either the French inventory of only dental stops or the English inventory of a dental-alveolar contrast, maintained the English contrast, but advanced early L2 French learners merged the dental and alveolar categories. These findings could not demonstrate a boundary shift, however, due to the lack of two categories per language.

1.3. THE CURRENT STUDY. Children of immigrants to the United States are an interesting case of simultaneous bilingualism. They are typically exposed to and taught their heritage language as well as English from birth, but the English used is of a non-American dialect such as English influenced by their specific heritage language. Use of their heritage language is limited to specific interlocutors (e.g. parents, older relatives) and domains (e.g. in the home), and is in addition to use of the non-American English dialect. As a result, English eclipses the heritage language as the speaker's dominant language, and the dialect of English received as input is varied. The participants in this study reflect these generalizations.

Indian Tamil (a Dravidian language spoken in the southern Indian state of Tamil-Nadu; distinct from Tamil varieties spoken in other countries) has two registers: the formal register used in schools, government and media communications, and all written publications; and the informal register used in all other spoken contexts. The formal and informal registers have different phonemic inventories and lexicons due to the formal register's rejection of Sanskrit loanwords and adapted phonology during the 1900s Tamil purist movement (Kailasapathy 1979). This resulted in diglossia – mutual unintelligibility – between the two registers (Ferguson 1959). Speakers who are not formally educated in the formal register never acquire it and thus are not literate in Tamil (Pillai 1965). The current study focuses on speakers of only the informal register of Tamil.

Informal Indian Tamil differs from English in its phonemic inventory of coronal stop consonants. American English contrasts between dental and alveolar POAs. The dental POA in American English occurs in the interdental fricative, which is contrastive with alveolar fricatives; as a stop, the dental POA is limited to context-dependent stop allophones of the interdental fricative. Indian Tamil contrasts between dental and retroflex POAs. The articulatory distance between the dental and retroflex locations is much greater than between the dental and alveolar locations, and thus Tamil likely has larger acceptable ranges for consonants produced in those categories. This suggests a Tamil dental category boundary which is more posterior than an English boundary. To investigate if this is true, this study tests if bilingual American English-Indian Tamil speakers demonstrate a double phoneme boundary with regard to coronal stop consonants.

The current study is the first to date to test for a POA double phoneme boundary in bilingual speakers. American English-Indian Tamil bilingual speakers presented with stimuli along a dental-retroflex continuum of voiceless plain coronal stops are predicted to place a category boundary between dental and alveolar stimuli in an English experiment context and a boundary between dental and retroflex stimuli in a Tamil experiment context. Such results would support the DLS Hypothesis that bilingual speakers use two separate phonemic inventories for each of their language modes. Visualizations of these category boundaries can be found in Figures 1 and 2 respectively.

Figure 1. Visualization of a hypothetical American English POA continuum. A category boundary exists between dental and alveolar phonemes. This equates to one of the language systems a bilingual speaker has according to the DLS Hypothesis.

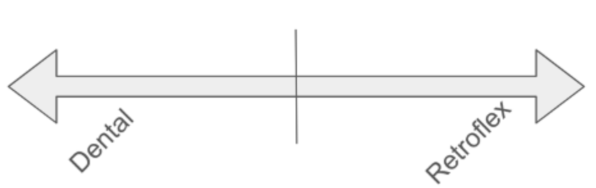

Figure 2. Visualization of a hypothetical Indian Tamil POA continuum. A category boundary exists between dental and retroflex phonemes. This equates to one of the language systems a bilingual speaker has according to the DLS Hypothesis.

Alternatively, these bilingual speakers may display three distinct categories (dental, alveolar, and retroflex) in both language contexts, lending support to an adult ULS. A visualization of these category boundaries can be found in Figure 3.

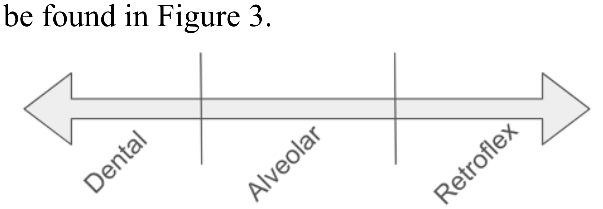

Figure 3. Visualization of a hypothetical American English and Indian Tamil bilingual speaker's POA continuum. A category boundary exists between dental and alveolar phonemes as well as

between alveolar and retroflex phonemes. This equates to the one language system a bilingual speaker has according to the ULS Hypothesis.

2. Methods. The current study investigates whether and how bilinguals categorize sounds ranging in POA differently in each of their language modes. For this purpose, simultaneous English-Tamil bilinguals were twice tested on their perceptual judgements of one continuous range of coronal stop consonants – once in an English-conducted experiment session and once in a Tamil-conducted experiment session.

2.1. STIMULI. Stimuli were constructed using Praat software (Boersma and Weenink, 2022) to create a 13-step continuum of dental to retroflex stop consonants. An example /at̪a/ and /aʈa/ produced by study personnel were measured for their burst frequency and formants 1, 2, and 3 transitions into the vowel, acting as continuum anchors. Burst frequency and formant transitions have been demonstrated to evoke change in POA perception (Syrdal 1983). To generate each step in the continuum, the base sound /at̪a/ had its transitions and burst replaced but the vowel steady states remained the same. Intermediate steps were assigned equally spaced values between the anchor measures (see Table 1, where Step 1 is the dental anchor and Step 13 is the retroflex anchor). The burst frequency of the example /at̪a/ was modified using Praat's Modify > Scale Peak feature, and the transitions were synthesized using the Formant Synthesizer Praat script (Chen 2021) which generates audio files of vowels with specified formant values. To synthesize the transitions, three time points were specified over the set 0.025 second duration, the sampling rate was set to 44100 Hz, and F0 was kept at a constant 200 Hz. Transitions into and out of the closure were identical but reversed.

		Formant 1			Formant 2			Formant 3		
Step	Burst	T.1	T.2	T.3	T.1	T.2	T.3	T.1	T.2	T.3
1	8000.0	885.0	850.0	690.0	1490.0	1565.0	1615.0	2600.0	2685.0	2780.0
2	7416.7	884.2	850.0	686.7	1499.2	1578.8	1642.1	2591.7	2677.9	2784.2
3	6833.3	883.3	850.0	683.3	1508.3	1592.5	1669.2	2583.3	2670.8	2788.3
4	6250.0	882.5	850.0	680.0	1517.5	1606.3	1696.3	2575.0	2663.8	2792.5
5	5666.7	881.7	850.0	676.7	1526.7	1620.0	1723.3	2566.7	2656.7	2796.7
6	5083.3	880.8	850.0	673.3	1535.8	1633.8	1750.4	2558.3	2649.6	2800.8
7	4500.0	880.0	850.0	670.0	1545.0	1647.5	1777.5	2550.0	2642.5	2805.0
8	3916.7	879.2	850.0	666.7	1554.2	1661.3	1804.6	2541.7	2635.4	2809.2
9	3333.3	878.3	850.0	663.3	1563.3	1675.0	1831.7	2533.3	2628.3	2813.3
10	2750.0	877.5	850.0	660.0	1572.5	1688.8	1858.8	2525.0	2621.3	2817.5
11	2166.7	876.7	850.0	656.7	1581.7	1702.5	1885.8	2516.7	2614.2	2821.7
12	1583.3	875.8	850.0	653.3	1590.8	1716.3	1912.9	2508.3	2607.1	2825.8
13	1000.0	875.0	850.0	650.0	1600.0	1730.0	1940.0	2500.0	2600.0	2830.0

Table 1. Stimuli specifications. Burst frequencies (Hz) and formant 2 and 3 transition start, middle, and end Timepoints (Hz), represented by T.#, for each stimulus along the POA continuum. Step 1 represents the most dental-like stimulus; Step 13 represents the most retroflex-like stimulus.

2.2. PROCEDURE. Participants took part in two 30-minute experiment sessions administered through the Gorilla Experiment Builder platform (Anwyl-Irvine et al. 2020) – one where instructions and tasks were presented in American English and one presented in Indian Tamil, counterbalanced for order of participation. In each session, participants completed three tasks.

The first task was always listening to a short story in the experiment language. The other tasks were an Identification Task and a Discrimination Task, whose presentation order was counterbalanced. For all tasks in either language, instructions were only presented auditorily due to participants having no literacy in Tamil.

In the story task, participants listened to a short story in the experiment language read aloud by native speakers of Indian Tamil or American English. The story content between languages was the same (a boy and a girl search a forest for a banana and save the forest from a fire), and word choice varied only to the extent necessary for clear translation. Both coronal stops in each language were represented in the stories. The English story contained 34 dental tokens and 40 alveolar tokens (voiced and voiceless included); the Tamil story contained 42 dental tokens and 23 retroflex tokens.

In the Identification Task, participants were first provided lexical references for the sounds relevant to the experiment language. The English version, having a dental-alveolar contrast, presented “thigh” as the dental referent and “tie” as the alveolar referent. The Tamil version, having a dental-retroflex contrast, presented “pathu” (“ten”) as the dental referent and “pattu” (“silk”) as the retroflex referent. The referents were always accompanied by a picture, present throughout the entire task to remind participants of the options. Participants were then asked to categorize the synthesized stimuli as containing either the sound in the dental referent or the sound in the non-dental referent. Participant decisions were recorded, and no feedback was provided. This task was designed to capture the location of the category boundary as well as the proportion of participants who agreed across the range of stimuli.

In the Discrimination Task, the synthesized stimuli were presented in an 4IAX paradigm (Pisoni 1975), where participants heard two pairs of stimuli and were asked to decide which pair contained an oddball (different) stimulus. In this study, each stimulus along the continuum was presented as the majority in a set containing an oddball stimulus either two more retroflex or two more dental than itself, such that each stimulus was presented as the majority in a set twice. For example, Stimulus 6 was presented in one trial as 6-6-6-8 and in a separate trial as 6-4-6-6. Position of the oddball stimulus in the set was systematically varied across trials. Each pair of stimuli was separated by a 1 second buffer for listener ease. Participant decisions were recorded, and no feedback was provided. This task was designed to capture one or more boundaries where participants were able to discern a difference between stimuli. Locations along the continuum with high proportions of participant correct responses indicated that the oddball stimulus laid across a category boundary from the majority stimuli.

Following completion of the experiment, participant language background was assessed using a questionnaire derived from the Language and Social Background Questionnaire (Anderson et al. 2018) asking participants to self-rate their usage and comfort with each of their languages.

2.3. PARTICIPANTS. 7 adult, simultaneous American English-Indian Tamil bilinguals were screened for: knowledge of American English and the informal register of Indian Tamil; residing in the United States of America since at least 3 years of age; no literacy or knowledge of the formal register of Indian Tamil; and if they had knowledge of any other language spoken in India, although knowledge of other languages was not disqualifying criteria. Participants had no known hearing impairments and were compensated $16 for their 1 hour of participation. The entire experiment was conducted remotely where participants were free to participate at a time, at a location, and using headphones or speakers of their choice.

Based on responses to the administered language questionnaire, participants had the following characteristics. Participants ranged between 25-32 years old. Five participants were born in the United States; the other two were born in India but immigrated to the United States by age 1 year old. Five participants self-identified as women; the other two self-identified as men. This information is summarized in Table 2.

P.	Age	Gender	Country of Birth
1	27	Woman	USA
2	28	Woman	USA
3	30	Man	USA
4	32	Woman	India
5	25	Man	USA
6	32	Woman	India
7	26	Woman	USA

Table 2. Participant demographic data. Participants' (P.) self-reported demographic data, including age, gender, and country of birth.

Five participants reported learning English from birth in the home; the other two reported learning English at age 3 years old upon beginning formal schooling. Six participants reported learning Tamil from birth in the home; only one reported learning Tamil at age 1 year old from their community. Participants reported using an increasing amount of English inside and outside the home from infancy until schooling, such that now through adulthood at least half of their language use is in English. This information is summarized in Table 3.

P.	English AoA	Tamil AoA	Language Use - Infancy	Language Use - Primary School
1	0	0	Half English, half Tamil	Mostly English
2	3	0	Mostly Tamil	Half English, half Tamil
3	0	0	Half English, half Tamil	Mostly English
4	3	0	All Tamil	Mostly English
5	0	1	Mostly English	Mostly English
6	0	0	Mostly Tamil	Half English, half Tamil
7	0	0	Mostly Tamil	Half English, half Tamil

Table 3. Participant language use data. Participants' (P.) self-reported language use data: age of acquisition (AoA) for English and Tamil; language use split between English and Tamil during infancy (options included "All Tamil", "Mostly Tamil", "Half English, half Tamil", "Mostly English", and "All English"); and language use split during primary school (options were the same as during infancy).

Participants self-rated their proficiency in English and Tamil on a 0-10 scale across four categories: speaking, listening, reading, and writing. All participants rated themselves at 10 for all English proficiency categories. Participants' Tamil proficiency ratings are displayed in Table 4. One participant rated their Tamil speaking as low (2); three participants rated their Tamil speaking as fair (4-6); two participants rated their Tamil speaking as high (9). All participants rated their Tamil listening as high (7-9). All but one participant rated their Tamil reading as 0; the other still rated their Tamil reading as low (3). All participants rated their Tamil writing as 0. It can thus be concluded that all participants had no literacy in Tamil, were not educated in the formal register, and only spoke the informal register.

P.	Tamil Speaking	Tamil Listening	Tamil Reading	Tamil Writing

1	9	9	0	0
2	9	9	0	0
3	6	7	0	0
4	4	7	3	0
5	2	8	0	0
6	5	8	0	0
7	5	8	0	0

Table 4. Participant Tamil proficiency data. Participants' (P.) self-rated Tamil proficiency across speaking, listening, reading, and writing. Rating scale options were integers from 0-10.

2.4. STATISTICAL ANALYSIS. Data were analyzed in RStudio using generalized linear mixed-effects models built with the lmerTest library (Kuznetsova et al. 2017). Both models examined relationships between the session language and the stimulus under consideration. The dependent variable in the Identification Task was the participant decision of "Dental" or "Not-Dental". The dependent variable in the Discrimination Task was whether the participant decision of the oddball pair was correct or incorrect. The random intercept was coded by participant ID number. Results are reported using p-values < 0.05, which were obtained using the glmer() function.

Data were also analyzed using Fisher's Exact Tests from the vcd library (Meyer et al. 2023). Fisher's Exact Tests, performed using the fisher.test() function, were used to compare proportions of participant responses for each stimulus between session language and for stimuli representing distinct phonemic categories. Results are reported using Bonferroni-corrected p-values.

3. Results. The data reported below are for the 7 participants who took part in the study. 2 participants completed an early version of the Identification Task that presented each stimulus only once; the other 5 participants completed a revised version of the Identification Task that presented each stimulus three times. No responses were excluded.

3.1. IDENTIFICATION TASK RESULTS. The Identification Task partially supported the hypothesis that bilingual speakers would demonstrate a double phoneme boundary for a POA continuum. There were 17 observations of participant responses per stimulus per language session. Fisher's Exact Tests performed on each stimulus compared across session language yielded insignificant differences in proportion of participant "Dental" responses (Bonferroni alpha level = $0.0038 < p$). However, Fisher's Exact Tests were performed comparing proportions of participant "Dental" responses for canonical dental (1), alveolar (6), and retroflex (13) stimuli. Stimulus 1 was chosen for being the most dental along the continuum; Stimulus 13 was chosen for being the most retroflex along the continuum; Stimulus 6 was chosen for falling within the expected range of the alveolar category in English and the expected range of the dental category in Tamil, thus representing a point where participant responses should differ between languages. These comparisons yielded the following results: in the English language context, there was a significant difference between dental and alveolar stimuli (Bonferroni alpha level = $0.016 > p$), but not between alveolar and retroflex stimuli ($p = 0.035$) or between dental and retroflex stimuli ($p = 0.53$); in the Tamil language context, there was a significant difference between alveolar and retroflex stimuli ($p < 0.016$), but not between dental and alveolar stimuli ($p = 0.035$) or between dental and retroflex stimuli ($p = 1.0$). Fisher's Exact Tests report statistical significance between Stimuli 1 and 6 in the English language session and Stimuli 6 and 13 in the Tamil language session. The percentages of participant "Dental" responses for each stimulus are visualized in Figure 4 below.

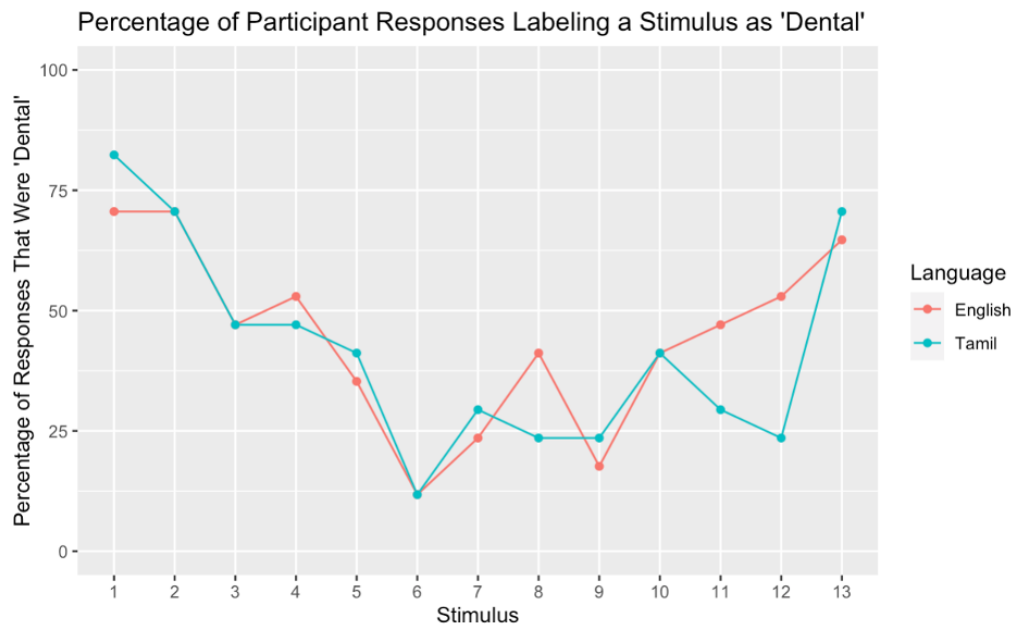

Figure 4. Percentage of participant responses that were "Dental" for each stimulus. 17 observations of participant responses per stimulus per language session.

A generalized linear mixed-effect model with fixed effects of session language, stimulus number and their interaction, as well as random intercept of participant was fitted over 444 observations across seven participants. The model had an Akaike Information Criterion (AIC) of 568.2, a marginal R^2 of 0.211, and a conditional R^2 of 0.277. Thus, this model does not account for all of the variation seen in the data. In terms of log odds, the effect size of session language on participants' proportion of "Dental" responses was -0.701 and not significant ($p = 0.119 > 0.05$). Participants were not more likely to label a stimulus as "Not-Dental" in the Tamil language session than the English language session for Stimulus 1. The effect sizes of Stimulus Number for Stimuli 5, 6, 7, and 9 were 1.596, 3.092, 2.315, and 2.595 respectively, and were significant ($p < 0.05$). Participants were more likely to label these stimuli as "Not-Dental" than they were Stimulus 1 (the most dental) in the English session. These stimuli therefore fall into a different category than "dental", accounting for the "alveolar" category. The effect sizes of stimulus number for Stimuli 10-13 were 1.326, 1.067, 0.812, and 0.186 respectively, and were not significant ($p > 0.05$), suggesting that stimuli in the retroflex range may have fallen into an ambiguous category in the English session. There were no significant effects of interaction between language session and stimulus number. The combination of session language and stimulus number does not predict participants' likelihood to label a stimulus as "Not-Dental" when compared to Stimulus 1 in the English session. Session language did not affect participant stimulus labeling.

Although participants appear to display three categories of coronal stop consonants rather than two in each language, each language session demonstrated only one statistically significant category boundary according to Fisher's Exact Tests. The other boundaries tested might be significant if tested with a larger sample size.

3.2. Discrimination task results. The Discrimination Task did not support the hypothesis that bilinguals would demonstrate different categories in each language session. There were 17 observations of participant responses per middle point of each stimulus set per language session. Middle point refers to the stimulus that falls between the two stimuli presented in a set (e.g. a set of 3-3-5-3 would have a middle point of 4). The percentage of correct participant responses for the sets' middle points are visualized in Figure 5 below. Fisher's Exact Tests performed on each stimulus compared across session language yielded no significant differences in participant correct responses (Bonferroni alpha level = 0.0045 < p).

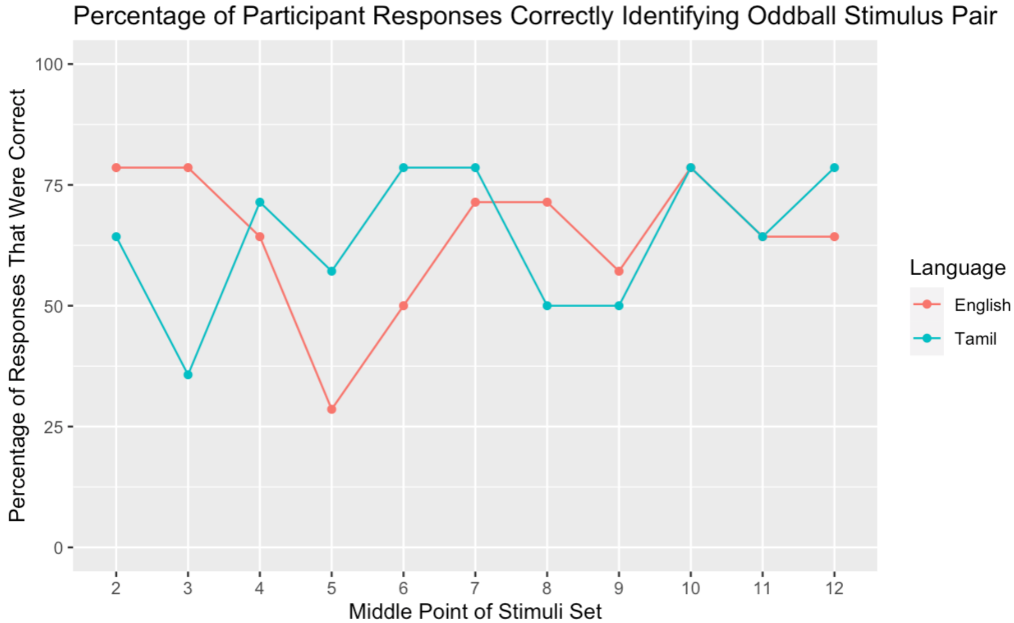

Figure 5. Percentage of participant responses correctly identifying the oddball stimulus pair containing the deviant stimulus across the middle point of each stimulus set. 14 observations of participant responses per stimulus per language session.

A generalized linear mixed-effect model with fixed effects of session language, stimulus number, and their interaction as well as random intercept of participant was fitted over 308 observations across seven participants. The model had an AIC of 415.3, a marginal R^2 of 0.110, and a conditional R^2 of 0.164. Thus, this model does not account for all of the variation seen in the data. In terms of log odds, the effect size of session language on participants' proportion of correct responses was -0.738 and not significant ($p = 0.397 > 0.05$) for MiddlePoint 2. Participants were not more likely to correctly identify the different stimulus in a set in the Tamil language session than the English language session. The effect size of MiddlePoint for MiddlePoint 5 was 2.316, which was significant ($p < 0.05$). This suggests that participants were less likely to identify the different stimulus in a set when the middle point was 5 in English compared to MiddlePoint 2, so this comparison likely fell within a phonemic category. However, no other middle points had significant effect sizes, so there was not a location along the continuum where participants were more likely to identify the different stimulus. Thus, there were no stimuli sets which clearly crossed phonemic category boundaries. There were no significant effects of interaction between language session and stimulus number. The combination of session language and stimulus number does not predict participants' likelihood to correctly identify the different stimulus in a set when compared to MiddlePoint 2. In total, there was not an effect of session language on participant stimulus discrimination performance.

4. Discussion. The results presented above may support the hypothesis that American English-Indian Tamil bilinguals would display different POA category boundaries in English and Tamil contexts, however it appears more likely that bilinguals instead use three categories in both language contexts, maintaining contrasts between dental, alveolar, and retroflex places-of-articulation. Further studies are required to fully discern the implications of these results.

4.1. THE IDENTIFICATION TASK. The Identification Task demonstrates that the interaction between session language and location along the POA continuum is not a significant predictor of how participants categorized stimuli. Thus, bilingual speakers' language mode did not influence classification of stimuli. This contrasts with the findings of prior literature (Elman et al. 1977; Bohn and Flege 1993; Garcia-Sierra et al. 2009; Casillas and Simonet 2018).

Participants displayed a clear category boundary between dental and alveolar stimuli in the English mode, but comparisons to the retroflex stimuli were not clear. In this binary forced-choice task, participants were not able to select the retroflex category for stimuli in that portion of the continuum. It was expected that stimuli in the retroflex range would be categorized as "Not-Dental" (alveolar) in the English language session, and significantly different from the dental stimuli. However, participant responses to stimuli in the retroflex range appeared to be near chance, and not significantly different from either the dental or alveolar categories. The presence of a distinct retroflex category could support a three-way, unitary categorization system.

In the Tamil language session, participants displayed a clear category boundary between alveolar and retroflex stimuli, however the retroflex stimulus used in the comparison (13) appears to deviate from the visual trend in Figure 4. The stimuli were created such that the continuum extends beyond the naturally-produced example dental and retroflex sounds. It may be the case that the most retroflex stimulus was not perceived as natural by the participants, creating confusion. There was not a significant contrast between dental and alveolar stimuli, however a larger, more appropriate sample size may yield different results.

Alternatively, the presence of only one significant contrast in each language mode suggests the presence of a double phoneme boundary and thus a DLS. If this is the case, the English boundary lies between the dental and alveolar stimuli, and the Tamil boundary lies further back between the alveolar and retroflex category. However, a larger sample size may indicate that the comparisons which were barely insignificant are actually also significant.

4.2. THE DISCRIMINATION TASK. The Discrimination Task yields inconclusive results, demonstrating a lack of clear categorical boundaries that does not align with the boundaries found in the Identification Task. Statistical evidence does not display an effect of language session or POA continuum location for most stimuli. This may be due to task difficulty, as previous categorical perception studies of the POA continuum which used a Discrimination Task spanned a range of bilabial to velar consonants (Liberman et al. 1957) which is much larger than the current study's range of dental to retroflex consonants. The smaller range with a similar number of stimuli creates smaller steps that may be more difficult to distinguish. It may also be that shorter buffers between stimulus pairs would aid memory load during the task and improve performance.

While the 4IAX paradigm was deemed appropriate for this study due to its sensitivity to acoustic differences, it may be that participants ignored phonemic category boundaries and instead responded to acoustic differences between stimuli. This would explain the higher than chance performance that participants displayed for most stimuli. Further work using the AXB paradigm, which encourages phonemic labeling, may yield clearer results (Repp 1984).

4.3. EFFECT OF ACOUSTIC FEATURES FOR POA VERSUS VOT. It should be noted that the results of this study, which partially support the ULS Hypothesis, deviate from behavioral findings of prior literature. The double phoneme boundary has been found in multiple studies of VOT (Elman et al. 1977; Bohn and Flege 1993; Garcia-Sierra et al. 2009; Casillas and Simonet 2018). While no study of VOT has captured a three-way contrast, it may be the case that POA continua are uniquely able to demonstrate one.

It may also be the case that VOT, which only varies by one acoustic measure, is a more reliable indicator of stimulus location along a continuum. The current study varied multiple acoustic measures in order to synthesize stimuli along the POA continuum, including burst frequency and multiple measures of formant 2 and 3 transitions. The synthesized stimuli were also created so each step along the continuum varied each acoustic measure by an even amount. This may not accurately reflect the true acoustic nature of each intermediate step, causing perceptual confusion among participants during the Discrimination Task and only canonical stimulus identification in the Identification Task. However, prior literature creating POA continua varied the same acoustic measures and found reliable phoneme identification by Hindi speakers for dental and retroflex consonants (Stevens and Blumstein 1975). Further work should be conducted on POA continua in order to reproduce these results and determine the true implications.

4.4. COMPARISON TO NEUROLOGICAL RESULTS. The results of the current study appear to align with research on the underlying neurological mechanism of categorical speech perception. The mis-match negativity (MMN) is an event-related potential (ERP) which is shown to capture perceived differences in acoustic speech signals (Näätänen 2001). The standard method to test the MMN is the oddball paradigm, which plays participants a series of the same stimulus and measures the ERP at the time of an introduced oddball (different) stimulus. Previous literature has shown that the MMN is stronger when the oddball stimulus crosses a native phonemic boundary, and weaker when the oddball stimulus is within the same phoneme class as the original stimulus (Dehaene-Lambertz 1997). Therefore, the MMN is shown to be language-specific.

In order for understood neurological mechanisms to align with the DLS Hypothesis, a bilingual speaker should demonstrate monolingual-like MMNs along the POA continuum in each language context. However, Tamminen et al. (2013) found that bilinguals displayed much slower MMNs than monolinguals in comparisons of vowel phonologies. This latency suggested slower processing of intertwined phonologies, supporting a ULS rather than a DLS. Additionally, MMN work conducted by Molnar et al. (2014) found that simultaneous bilinguals maintained all of their native language categories at the same time rather than assimilating them to the language context. Therefore, the results of the current study, which support a ULS with regard to POA, align with neurological evidence.

4.5. EXPLANATIONS FOR ALVEOLAR CATEGORY IN TAMIL AND RETROFLEX CATEGORY IN ENGLISH. Molnar et al. (2014) also found that simultaneous bilinguals were able to develop an internal language context when presented with speech sounds that are standard to one of their native languages, corroborated by the warnings of Garcia-Sierra et al. (2009). In the current study, the presented stimuli may have induced internal language contexts in the participants that contradicted the language context set by the experiment session. Thus, when the stimulus was in the alveolar range of perception, an English internal language mode was induced, causing perception of the alveolar stop even in the Tamil language session. When the stimulus was in the retroflex range, a Tamil internal language mode was induced, causing perception of the retroflex stop even in the English language session. General Indian English, especially Tamil English, uses retroflex stop consonants in place of alveolar (Wiltshire and Harnsberger 2006), making the retroflex stop a salient marker of the Indian English variety as well. Either line of reasoning would explain the presence of a retroflex category in the English session of the current study.

Another mechanism is necessary to explain the lack of retroflex responses to retroflex stimuli in the Tamil language session. All participants reported use of English in a majority of daily interactions and increasing English dominance through development into adulthood. The English dominance may have prevented a Tamil language mode. Alternatively, there may have been influence from participants' other languages. Multiple participants reported some knowledge of Hindi, whose retroflex stop consonants are closer to alveolar than those of Tamil (Ladefoged and Bhaskararao 1983). Participants may have perceived the alveolar range of stimuli to be the General Indian English retroflex, and the Tamil retroflex to be unclear as a result. Some participants also reported knowledge of Malayalam, which has a three-way phonemic contrast between dental, alveolar, and retroflex stops (Dart and Nihalani 1999). While not mutually intelligible, Malayalam and Tamil may have been perceptually close enough that participants perceived the three Malayalam categories instead.

4.6. FUTURE WORK. A clear limitation of the current study is the small sample size of seven participants. As such, the results of this study should be taken as pilot work and reproduced with at minimum 30 participants. A greater sample size may yield more significant comparisons or may display greater variability such that the demonstrated effects are no longer significant.

Implications of the current study should also be clarified with additional experiments. Namely, as prior work had found a VOT phonemic boundary shift in both bilinguals and monolinguals, it should be tested whether the POA three-way contrast shown here in bilinguals is present in English and Tamil monolinguals as well. If so, these findings would support the PAM over the ULS Hypothesis.

5. Conclusion. The current study did not find a double phoneme boundary in American English-Indian Tamil bilinguals' POA continuum. Instead, results appeared to show a three-way contrast between dental, alveolar, and retroflex stop consonants in both English and Tamil language contexts. While these findings deviate from prior work, they are supported by neurological work on categorical perception. The DLS Hypothesis is tentatively dismissed in favor of an adult ULS, however future work must be done to disentangle the ULS from the monolingual-inclusive PAM.

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