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Coarticulation and Transitional Probability in Japanese Perceptual Epenthesis

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Abstract

This study examines the roles of coarticulation and transitional probability in Japanese perceptual epenthesis, where listeners perceive illusory vowels to resolve phonotactically illegal sequences. We replicated and extended a previous experiment showing that Japanese listeners tend to insert /u/ or /i/ in illicit sequences like /eʃpo/ and /et͡ʃpo/, influenced by the transitional probability of the preceding consonant. To isolate the effects of coarticulation, we modified /et͡ʃpo/ stimuli by removing the closure of the affricate /t͡ʃ/. Participants categorized and discriminated between these stimuli in two experiments. Results indicated that even with reduced coarticulatory influence, the patterns of /u/ and /i/ epenthesis persisted, underscoring the significant role of transitional probability in perceptual epenthesis. This study clarifies how Japanese listeners utilize both coarticulation and transitional probability to perceptually adapt illicit consonant clusters into phonotactically licit sequences.

Index Terms: Perceptual Epenthesis; Japanese; Speech Perception; Transitional Probability; Coarticulation

1. Introduction

Perceptual epenthesis is a phenomenon where listeners perceive illusory vowels within sequences that violate the phonotactic rules of their native language [1,2]. This process is a perceptual strategy to resolve illicit sequences into phonotactically legal sequences. For instance, Japanese listeners often hear an epenthetic /u/ in sequences like /ebzo/, perceptually transforming it into /ebuzo/ to conform to Japanese phonotactics which typically prohibits non-homorganic consonant clusters [1]. This perceptual adjustment is not unique to Japanese but is observed across various languages, each with its own tendencies for epenthetic vowel selection. In Japanese, the most common epenthetic vowel is /u/, which is phonetically minimal due to its short duration and tendency to undergo devoicing [3].

In this study, we replicate and extend an earlier experiment on Japanese perceptual epenthesis [4], which showed that listeners epenthesized /u/ or /i/ depending on the preceding consonant in phonotactically illicit tokens of /eʃpo/ and /et͡ʃpo/. This was argued to be the result of the relative transitional probability of CV sequences. Transitional probability is the likelihood of one sound following another which in turn is used to calculate Surprisal and Entropy. While both /t͡ʃi/ and /ʃi/ are reasonably high-frequency diphones (low Surprisal [5]), the context following /t͡ʃ/ is less chaotic (low Entropy [5]) than the context following /ʃ/ in Japanese, and the former was found to elicit a relatively high rate of non-default /i/-epenthesis. Yet, an alternative account may be that the coarticulatory influence of the preceding vowel /e/ enhances /i/-epenthesis, as demonstrated in [6]. This coarticulation might be obstructed by the closure in the affricate /t͡ʃ/, potentially affecting the selection of the epenthetic vowel. To investigate this possibility, we modified the /et͡ʃpo/ stimuli by removing the closure at the beginning of the affricate, which should reduce the coarticulatory influence of the preceding vowel. In the editing process, we took an average of the unmodified fricatives' duration as a reference and aimed to mirror that average by extending the frication in the modified stimuli, ensuring that the editing process did not present perceptible signs of alteration. We then ran the same experiment with the inclusion of the modified stimuli to determine whether the observed patterns of /u/ and /i/ epenthesis persist under these modified conditions.

1.1. Epenthetic Vowels

The choice of epenthetic vowel can differ significantly between languages, influenced by a range of phonological, statistical, and acoustic factors. For example, in Brazilian Portuguese, the shortest vowel, /i/, functions as the default epenthetic segment, contrasting with the /u/ in Japanese [2]. In Korean, the dominant epenthetic vowel is /ɨ/; however, listeners may perceive an alternate epenthetic vowel /i/ in sequences where the production of the dominant vowel would violate Korean phonotactics [7]. Spanish listeners have been found to insert an /e/ in sequences that disallow consonant clusters [8], and English speakers may use the schwa (/ə/) [9].

A seemingly important feature of epenthetic vowels is that the target vowel or vowels can sometimes be omitted without changing the meaning of words. For example, in English the centralized schwa is both the target for vowel reduction and perceptual epenthesis. The different ways that the word *family* can be pronounced illustrates this concept because whether one says [fæmɪli], [fæməli], or [fæmli], the meaning of the word remains unchanged. In Japanese, high vowels (/i/ and /u/) can undergo a process known as vowel devoicing under certain phonological conditions. This devoicing occurs when high vowels are situated between voiceless consonants or at the end of a word following a voiceless consonant. Despite the devoicing, and sometimes even deletion (see [3]), these vowels are still considered to be part of the underlying phonological representation of the word. As a result, the meaning of the word remains unchanged even when the high vowel is not audibly pronounced. This phenomenon is a part of the native speaker's phonological knowledge and does not typically lead to confusion or ambiguity in understanding the spoken language.

Another seemingly important feature in epenthetic vowel selection is coarticulation, where phonotactically illegal consonant clusters are affected by acoustic cues from adjacent vowels. For example, [6] used an identification task to assess the quality of epenthetic vowels perceived by Japanese listeners in illegal consonant clusters with varying amounts of coarticulation. They created cross-spliced stimuli where the

coarticulation present in the consonant cluster did not match the quality of the flanking vowel. Two types of clusters were used: /hp/ and /kp/, with the former containing larger amounts of resonances from the preceding vowel. The results showed that both the flanking vowel and coarticulation influenced the quality of the perceived epenthetic vowel, but the influence of coarticulation was much larger for /hp/ clusters because the vowel identity was better signaled through the fricative in /hp/ clusters compared to the stop in /kp/ clusters.

Transitional probability also seems important in the selection of epenthetic vowels during perceptual epenthesis. This concept refers to the likelihood of a particular vowel following a given consonant based on a listener's linguistic experience. [4] found that Japanese listeners were more likely to perceive an epenthetic /i/ following the consonant clusters /ʃ/ and /t͡ʃ/ due to the higher transitional probability associated with these combinations as opposed to /g/. Transitional probability was calculated using the Surprisal and Entropy [5] equations, where Surprisal indicates how unexpected a vowel is after a consonant, and Entropy reflects the uncertainty or variability of which vowel might follow. For instance, the Surprisal values for /ʃi/ and /t͡ʃi/ are lower than those for /ʃu/ and /t͡ʃu/, meaning that /i/ is less surprising and more predictable after /ʃ/ and /t͡ʃ/ than /u/ is. Additionally, the Entropy for /t͡ʃ/ is lower than for /ʃ/, indicating that the vowel following /t͡ʃ/ is more predictable. The results showed that Japanese listeners were more likely to experience /i/ epenthesis following /t͡ʃ/ than following /ʃ/ despite both having a high transitional probability (or low Surprisal) with /i/. In other words, despite /u/ being the default target for perceptual epenthesis in Japanese, both /t͡ʃ/ and /ʃ/ elicited /i/ epenthesis with a slightly stronger effect for /t͡ʃ/ that reflects both the transitional probability of /t͡ʃi/ (Surprisal), and the overall probability of the context following /t͡ʃ/ (Entropy).

In this study, we recreate the experiments featured in [4] with the inclusion of modified stimuli where those stimuli have been altered to minimize the coarticulatory influence of the preceding vowel. Specifically, we removed the closure at the beginning of the affricate /t͡ʃ/ in /et͡ʃpo/, /et͡ʃipo/, and /et͡ʃupo/ stimuli which should reduce the carryover effects of coarticulation and allow us to better isolate the role of transitional probability in epenthetic vowel selection. By comparing the patterns of /u/ and /i/ epenthesis in both the original and modified stimuli, we aim to determine whether the previously observed tendencies are robust to changes in coarticulatory context. This approach allows us to disentangle the relative contributions of coarticulation and transitional probability to the perceptual epenthesis process, providing a clearer understanding of how Japanese listeners resolve phonotactically illegal sequences in their native language.

2. Method

All models were constructed in R [10]. All data and code relating to this project can be found here: https://osf.io/mduc9/?view_only=e20f9f4d92d54044b0ab941122b3d24a. The following experiments have ethics approval from the Nagoya University of Commerce and Business (#23065).

2.1. Stimuli

The stimuli for both experiments are shown in Table 1. Other than the modified tokens, these are the exact same stimuli as used in [4]. The medial /C/ and /CV/ sequences were embedded in in a nonce frame constructed from /e/, /p/, and /o/ because these phonemes occur infrequently in Japanese and thus limit unintended variability to the dataset beyond those factors deliberately manipulated. Tokens were constructed into either licit /eCVpo/ or illicit /eCpo/ sequences. Vowels presented in the epenthetic position in licit sequences were either /i/ or /u/ and consonants preceding the epenthetic position were /ʃ/ or /t͡ʃ/. Three female Australian English speakers produced five tokens of each target with initial stress. The first and fifth tokens were discarded. Recordings were conducted in the Horwood recording studio at the University of Melbourne and were recorded in mono with 16-bit resolution.

Table 1. *List of stimuli used in both experiments. Modified affricates are explained in the following paragraph.*

Token	/eCpo/	/eCupo/	/eCipo/
Fricative	/eʃpo/	/eʃupo/	/eʃipo/
Affricate	/et͡ʃpo/	/et͡ʃupo/	/et͡ʃipo/
Modified Affricate	/e(t)ʃpo/	/e(t)ʃupo/	/e(t)ʃipo/

All tokens with the affricate /t͡ʃ/ were manipulated in Praat. To edit the /t͡ʃ/ tokens to resemble /ʃ/ tokens (represented with /(t)͡ʃ/), we first identified and spliced out the closure portion of the affricate (highlighted in Figure 1), from near the beginning of the drop in energy after the /e/ to just after the release in /t͡ʃ/. Then, we extended the remaining aperiodic portion by splicing a section of it from the middle of the aperiodic period into the existing fricative to mask any acoustic cues of the edit, and to emulate the longer duration characteristic of the [ʃ] in /ʃ/ tokens. Each token was carefully analyzed to ensure that the editing process did not introduce any additional pops or other indication of token manipulation. Although considerable care was taken in this process, the average unmodified fricative length (M = 118ms, SD = 23) was slightly longer than the average modified fricative length (M = 114ms, SD = 22).

2.2. Participants

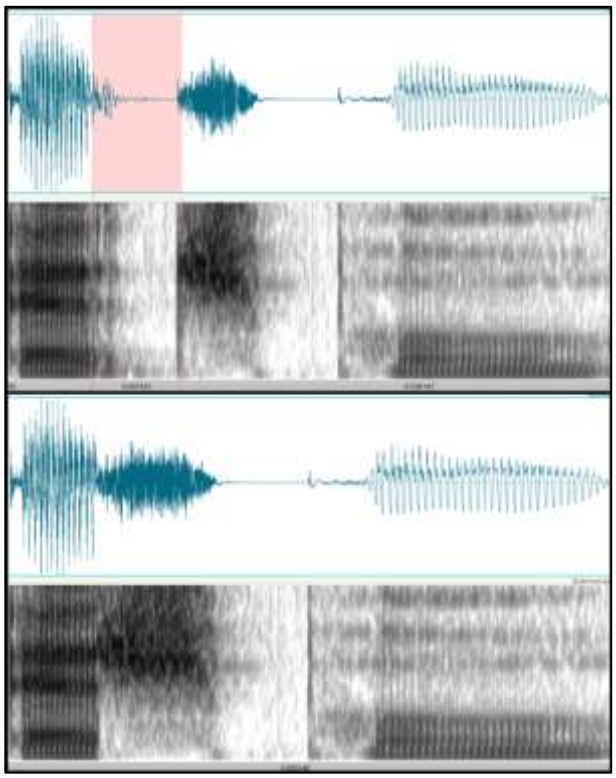
We recruited 44 Japanese undergraduate students from the Nagoya University of Commerce and Business started the experiment. All participants reported being monolingual Japanese speakers. Two participants requested to end the experiment prior to completion and their data was discarded. Of the 42 participants that completed the experiment, 9 students reported having at least one parent with a native language other than Japanese. These include 4 Brazilian Portuguese, and one each Peruvian Spanish, Turkish, English, Urdu, and Mandarin Chinese. Given that /i/ is the default epenthetic vowel in Brazilian Portuguese [2], we eyeballed the data from those participants with Brazilian Portuguese speaking parents in the AXB discrimination experiment and found their results to be different to those from the other participants. We therefore exclude the results of these 4 participants unless otherwise noted. Participants signed consent forms prior to starting the experiment and were not compensated for their time.

2.3. Procedure

Both experiments were conducted using Psyscope X on iMacs running a 32bit operating system. Six computers were set up in a laboratory and the experiments were conducted on a maximum of six participants at a time. Computers were equipped with noise cancelling headphones, keyboards, and mice. Prior to the experiments, participants completed a short biographical survey. The experiments took less than 15 minutes

to complete. The first author gave instructions in Japanese and waited for all participants to complete Experiment 1 prior to explaining the procedure for Experiment 2.

Figure 1. *Waveform and spectrogram of an /etʃ͡po/ token with the highlighted closure segment that was removed to transform the affricate /t͡ʃ/ into the fricative /ʃ/ (top). Modified /e(t͡)ʃpo/ token after removal of the closure and extension of the fricative (bottom).*



2.3.1. Experiment 1: Categorization

In the categorization experiment, participants were exposed to the stimuli listed in Table 1. They were asked to categorize each string into one of four categories (/et͡ʃipo/, /et͡ʃupo/, /eʃipo/, and /eʃupo/), which were presented as on-screen buttons with hiragana labels (えちぽ, えちゅぽ, えしぽ, and えしゅぽ). Participant responses were recorded via mouse click. After assigning a category, the token would be replayed, and the participant would be shown a seven-point Likert scale. They were asked to assign a score according to how well the token fit the assigned category. The experimental strings were drawn randomly from a library of 81 tokens, with three repetitions of each of the nine stimuli from each of the three speakers. Each token was presented to participants one time unless they failed to respond within 3500ms, in which case the trial would be randomly inserted into the remainder of the experiment.

2.3.2. Experiment 2: Discrimination

In the discrimination experiment, participants were exposed to AXB triads made up of three tokens listed in Table 1. In this experiment, participants were asked to indicate whether the second token best matched the first or third token by pressing either "1" or "3" on a keyboard. To avoid sequence bias, the individual tokens for each AXB triad were counterbalanced and occurred in every position of the triad. Each triad comprised one token from each of the three speakers, determined by partial Latin square (123, 132, 213, 231, 312, 321, where the numbers denote a speaker), and each of these sequences was organized into four different triad sequences (AAB, ABB, BAA, BBA, where the letters denote a stimulus token). Each trial was drawn three times at random from this array of 24 triads, resulting in a total of 72 trials. Participants had a 2000 ms response window to respond. If they failed to respond within this time, the missed trial was replayed at a random time during the remainder of the experiment.

3. Results

3.1. Categorization

In the categorization experiment, the unmodified illicit tokens (/et͡ʃpo/ and /eʃpo/) behave similarly with both exhibiting around a 60/40 split with a preference for /u/ classification and a reasonably high average fit score (~6). As to the modified tokens, 24.2% of them were classified as /t͡ʃ/ tokens, suggesting that some elements of the affricate remain despite splicing out the closure and extending the fricative. The e(t͡)ʃpo stimuli were more often classified to the /eʃupo/ (53.24%) than the /eʃipo/ (21.18%) category. The fit scores for the modified stims were slightly lower (~5.5) than the unmodified stims.

Table 2. *Results of the Categorization experiment. Categories run across the top of the table; tokens are to the left. The first number represents the percentage of samples assigned to that category; the second number is the average fit score. Shaded cells reveal majority classification.*

		/et͡ʃipo/	/et͡ʃupo/	/eʃipo/	/eʃupo/
/eCipo/	et͡ʃipo	87.32% (6.17)	9.14% (4.90)	2.06% (4.71)	1.47% (3.80)
	eʃipo	0.58% (1.00)	0.29% (3.00)	92.42% (6.02)	6.71% (4.65)
	e(t͡)ʃipo	16.08% (5.75)	2.92% (3.00)	76.02% (5.67)	4.97% (5.59)
/eCupo/	et͡ʃupo	7.87% (5.93)	90.67% (5.83)	0.87% (5.00)	0.58% (4.00)
	eʃupo	0.58% (4.00)	2.04% (5.00)	2.04% (3.71)	95.34% (6.06)
	e(t͡)ʃupo	4.97% (5.53)	23.10% (5.66)	6.73% (4.96)	65.20% (5.62)
/eCpo/	et͡ʃpo	39.77% (5.93)	59.65% (5.97)	0.58% (2.50)	0%
	eʃpo	1.16% (5.75)	2.33% (3.25)	37.50% (5.67)	59.01% (5.99)
	e(t͡)ʃpo	10.88% (5.08)	14.71% (5.06)	21.18% (5.49)	53.24% (5.48)

3.2. Discrimination

Table 3. *Results of the Discrimination experiment. Acc% represents the discrimination accuracy in AXB trials.*

Contrast pair		Acc%
[et͡ʃpo]	[et͡ʃupo]	65.79%
	[et͡ʃipo]	63.82%
[eʃpo]	[eʃupo]	57.68%
	[eʃipo]	69.96%
[e(t͡)ʃpo]	[e(t͡)ʃupo]	57.02%
	[e(t)ʃipo]	64.91%

Using the *lme4* package [11], we analyzed these data in a logistic mixed-effects model with contrast-coded fixed factors Consonant (/t͡ʃ/ vs. /ʃ/ vs. /(t͡)ʃ/, Vowel (/i/ vs/ /u/) and their interaction, and a random intercept for Participant. The Anova function in the *Car* package [12] was used to establish statistical significance, and post-hoc analyses with corrections for multiple comparison were run in the *emmeans* package [13].

The model revealed an effect of Vowel (β = 0.13, *SE* = 0.04, z = 3.31, $\chi^2(2)$ = 11.0, p<.001), with overall higher accuracy for the pairs with /i/ than for those with /u/, and a Consonant × Vowel interaction (/t͡ʃ/:/i/: β = -0.18, *SE* = 0.06, z = -3.11; /ʃ/:/i/: β = 0.14, *SE* = 0.06, z = 2.46; /(t͡)ʃ/:/i/: β = 0.04, *SE* = 0.06, z = 0.65; χ^2 = 10.7, p < .005). Post-hoc analyses revealed that for the affricate accuracy did not differ according to the vowel (β = -0.09, *SE* = 0.14, z < 1), while for the fricative and the modified affricate accuracy was higher for pairs with /i/ than for those with /u/ (fricative: β = 0.55, *SE* = 0.14, z = 3.90; p < .001; modified affricate: β = 0.34, *SE* = 0.14, z = 2.48; p < .02). In addition, neither in the context of /i/ nor in that of /u/ was there a difference in accuracy between the fricative and the modified affricate (/i/: β = 0.24, *SE* = 0.14, z = 1.65; p > .1; /u/: β = 0.03, *SE* = 0.14, z < 1).

With a caveat of very small sample size, we also analyzed the possible influence of likely exposure to Brazilian Portuguese (BP), whose default epenthetic vowel is /i/ rather than /u/ [2]. Thus, we included the four participants with at least one native Brazilian Portuguese speaking parent in the sample and ran the same model as before but with the addition of contrast-coded BP (yes vs. no) and all its interactions. The mean accuracy scores of the added participants were 83.3% and 66.7% for the affricate when the vowel was /u/ or /i/, respectively, 77.1% and 72.9% for the fricative, and 68.8% and 72.8% for the modified affricate. The model revealed the same main effect of Vowel and its interaction with Consonant as found in the previous model. In addition, there was an effect of BP, with overall higher accuracy by the participants with a Brazilian Portuguese speaking parent (β = 0.50, *SE* = 0.22, z = 2.26, $\chi 2$ = 5.10, p = 0.024), and, crucially, a BP × Vowel interaction (β = -0.29, *SE* = 0.14, z = -2.04, χ^2 = 4.16, p < 0.05). Post-hoc analyses revealed that contrary to the other participants, those with a Brazilian Portuguese speaking parent did not perform differently in the two vowel contexts (β = -0.32, *SE* = 0.27, z = -1.15, p > 0.1). In addition, in the context of /u/ the participants with a Brazilian Portuguese speaking parent had higher accuracy scores than the other ones (β = -0.79, *SE* = 0.27, z = -2.94, p < .004), while there was no difference in the context of /i/ (β = -0.21, *SE* = 0.26, z < 1).

4. Discussion

This study aimed to disentangle the relative contributions of vowel coarticulation and transitional probability to the perceptual epenthesis process by Japanese listeners in clusters starting with a fricative vs. an affricate. A previous study found that a cluster starting with /t͡ʃ/ yields more /i/-epenthesis than one starting with /ʃ/ [4]. By modifying the closure segment of the affricate /t͡ʃ/ in the stimuli used in that study, we created tokens that were predominantly classified as /ʃ/ stimuli. These modified tokens were then used together with the original tokens with /t͡ʃ/ and /ʃ/ in an AXB discrimination experiment. For the original tokens we qualitatively replicated the response pattern observed in [4], i.e. for the /ʃ/ tokens higher accuracy (hence less epenthesis) in the condition with /i/ than that with /u/, and no difference for the /t͡ʃ/ tokens. Crucially, even though as far as /i/-epenthesis is concerned the results for the modified tokens were numerically in between those for the original /ʃ/ and /t͡ʃ/ tokens, overall, the results for these tokens were statistically indistinct from those for the /ʃ/ tokens. These results confirm that transitional probability plays a significant role in epenthetic vowel quality. Thus, while coarticulatory cues are important [6], they are not the sole determinant in epenthesis patterns. Instead, transitional probability also influences the selection of the epenthetic vowel, contributing to the overall perceptual process.

The low classification accuracy of the pairs [eʃpo]-[eʃupo] and [e(t͡)ʃpo]-[e(t͡)ʃupo]—compared to other pairs—suggests that /u/ is a much stronger target for epenthesis in Japanese. This is not a particularly novel finding given that other studies [e.g., 2] have shown that Japanese listeners prefer /u/ in these contexts. Future studies might also include contrasts where unmodified tokens are tested against modified tokens, such as [e(t)ʃpo]-[eʃupo] and [e(t)ʃpo]-[eʃipo], to further explore the nuances of coarticulatory effects.

Finally, although we had not planned to investigate this issue, the presence of 4 participants with at least one native Brazilian Portuguese speaking parent allowed us to tentatively examine the influence of likely exposure to this language. That is, while these participants reported being monolingual, they had likely been exposed to BP to at least some extent from birth on. We found that these participants showed overall higher accuracy in the context of /u/ and hence perceived more /i/-epenthesis than the other participants. This finding is reminiscent of previous research showing that the default epenthetic vowel in second-generation Japanese immigrants in Brazil who have acquired both Japanese and Brazilian Portuguese during childhood is /i/. [14]. Yet, with our small sample size and in the absence of a language background questionnaire it is unwarranted to draw any conclusion. Future research should investigate whether the quality of the default epenthetic vowel can be influenced by early language exposure to Brazilian Portuguese even in reportedly monolingual Japanese speakers.

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