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Abstract

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Dedication

Acknowledgements

I want to thank...

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Chapter 1

Introduction

Brainstorming

- Best / Kuhl / Flege ...
- early process (input syst) vs late process (orthography, differences in production ...)
- Things mentioned in chapter 2
 - one-step vs. two-step (Berent2007, Monahan2009)
 - P-map
- articulation on perception (D'Ausilio, etc)

Chapter 2

Epenthetic vowel quality: Acoustics, phonetics, phonology

While there seems to be a consensus concerning the presence of perceptual misperceptions due to discrepancies between native phonotactics and non-native phoneme structures, the mechanisms underlying these phenomena are subject to more debate. In the case of perceptual (vowel) epenthesis, certain proposals (e.g., [Berent et al., 2007, Monahan et al., 2009]) hypothesize that the process is constituted of two steps in which the quality of the epenthetic vowel is determined by a language-specific grammar after an initial parsing. In particular, good candidate vowels might be those that are subject to vowel reduction or deletion in the native language. In contrast, one-step proposals (e.g., [Dupoux et al., 2011]) argue that the identity of the epenthetic vowel is determined in the process of parsing the input. In particular, parsing becomes an optimisation problem where the optimal output is the one maximising the acoustic match to the input and the likelihood of the phonemic sequence in the native language. Results by [Dupoux et al., 2011] support one-step theories, as they were able to modulate the identity of the epenthetic vowel without changing the segmental structure of the input stimuli.

[Dupoux et al., 2011] manipulated acoustic details in their stimuli, which led to the conclusion that coarticulation cues influenced epenthetic vowel quality. However, several question remain: How does this influence compare to other influences such as those of an abstract grammar? Can we reproduce these modulations of epenthetic vowel quality on naturally produced stimuli? And finally, if acoustics are quintessential to choosing epenthetic vowel quality, does this mean that they are sufficient to do so?

In **section 2.1** a perceptual experiment aims to disentangle the contributions of phonetic categories and acoustic details on epenthetic vowel quality. Participants are asked to report their choice of epenthetic vowel (if any) within consonant clusters in stimuli where the acoustic information contained in the cluster may be in disagreement with the identity of neighbouring vowels. Information theoretic measures allow to quantify the influence of both neighbouring phonetic categories and acoustic details.

In **section 2.2** I investigate the possibility of predicting epenthetic vowel quality in Brazilian Portuguese (BP) and Japanese (JP) using a production-based exemplar model of perception. This type of model predicts the quality of a vowel epenthized within the cluster of a stimulus based solely on the acoustic similarity of said /CC/ cluster to /CVC/ exemplars produced by native speakers of BP or JP. From this modelling approach we can evaluate the influence of pure acoustics on effects such as default epenthetic vowel quality and modulations induced by neighbouring vowels, with naturally produced stimuli that have not been manipulated.

2.1 Which epenthetic vowel?

Phonetic categories versus acoustic detail in perceptual vowel epenthesis

The following section is a modified version of the following journal article:

Guevara-Rukoz, A., Lin, I., Morii, M., Minagawa, Y., Dupoux, E., & Peperkamp, S. (2017). Which epenthetic vowel? Phonetic categories versus acoustic detail in perceptual vowel epenthesis. The Journal of the Acoustical Society of America, 142(2), EL211-EL217.

Abstract This study aims to quantify the relative contributions of phonetic categories and acoustic detail on phonotactically-induced perceptual vowel epenthesis in Japanese listeners. A vowel identification task tested whether a vowel was perceived within illegal consonant clusters and, if so, which vowel was heard. Cross-spliced stimuli were used in which vowel coarticulation present in the cluster did not match the quality of the flanking vowel. Two clusters were used, /hp/ and /kp/, the former containing larger amounts of resonances of the preceding vowel. While both flanking vowel and coarticulation influenced vowel quality, the influence of coarticulation was larger, especially for /hp/.

2.1.1 Introduction

Our auditory perceptual system is tuned to the sound system of our native language, resulting in impoverished perception of nonnative sounds and sound sequences [Sebastián-Gallés, 2005]. For instance, in Japanese, a vowel can only be followed by a moraic nasal consonant or by a geminate consonant. As a consequence, Japanese listeners tend to perceive an illusory, epenthetic, /u/ within illegal consonant clusters [Dupoux et al., 1999, Dehaene-Lambertz et al., 2000, Dupoux et al., 2001, Monahan et al., 2009, Dupoux et al., 2011, Guevara-Rukoz et al., 2017] and it is evident in loanword adaptation as well (e.g. the word 'sphinx' is borrowed in Japanese as /sufiNkusu/). Similar effects have been documented in other languages, with different epenthetic vowels (/i/ in Korean [Kabak and Idsardi, 2007, Berent et al., 2008, de Jong and Park, 2012]; schwa in English [Berent et al., 2007, Davidson and Shaw, 2012]; /i/ in Brazilian Portuguese [Dupoux et al., 2011, Guevara-Rukoz et al., 2017]; and /e/ in Spanish [Hallé et al., 2014]). Even within languages, there sometimes is variation in the quality of the epenthetic vowel; for instance, in Japanese, the epenthetic vowel can in certain contexts be /i/ or /o/ [Mattingley et al., 2015, Guevara-Rukoz et al., 2017].

The factors that determine the quality of the epenthetic vowel are still unclear. There is evidence that local acoustic cues in the form of vowel coarticulation play a role. Specifically, using artificial consonant clusters obtained by completely removing an inter-consonantal vowel, [Dupoux et al., 2011] found that the quality of the removed vowel – traces of which are present in the neighboring consonants – influences the quality of the epenthetic vowel. Other studies, however, have argued for an influence of phonological factors, such as the legality of the resulting repair at the phonotactic level [Mattingley et al., 2015] or the presence of phonological alternations in the language [Durvasula and Kahng, 2015]. Determining the source

of epenthetic vowel quality is important at a theoretical level, because it can shed light on the computational mechanisms underlying the perception of speech sounds. For instance, [Dupoux et al., 2011] argued that coarticulation effects cannot be accounted for by two-step models, in which the repair of illegal sequences follows that of phoneme categorization, while they are in accordance with one-step models, in which phoneme categorization takes phonotactic probabilities into account.¹ However, [Dupoux et al., 2011] only assessed the presence of acoustic effects, without investigating a possible role of categorical effects. Here, our aim is to quantify the relative contributions of categorical and acoustic effects on epenthetic vowel quality by directly comparing these two types of effect.

We focus on perceptual vowel epenthesis following /h/. This case is ideally suited for our objective as in Japanese loanwords these fricatives are typically adapted by adding a ‘copy’ of the preceding vowel when they occur in a syllable coda. For instance, ‘*Bach*’, ‘(*van*) *Gogh*’, and ‘*Ich-Roman*’ are adapted as /bah:a/, /goh:o/, and /ih:iroman/. In work on loanword adaptations, cases of vowel copy in epenthesis have been explained as a result of the spreading of phonological features from the preceding vowel onto the epenthetic vowel (i.e., vowel harmony), for instance in Shona, Sranan, and Samoan [Uffmann, 2006], and Sesotho [Rose and Demuth, 2006]. In speech perception, however, this pattern could be based either on phonetic categories, i.e. the preceding vowel itself, or on acoustic detail, i.e. traces of this vowel that are present in /h/, as laryngeal fricatives such as /h/ contain acoustic information relative to formants of surrounding vowels [Keating, 1988]. Using an identification task, we tease apart these two explanations by independently manipulating the categorical context in which /h/ occurs and the acoustic realization of this segment, using cross-splicing. As a control, we also use stimuli with /k/, which are expected to give rise to more default /u/-epenthesis because they contain less coarticulation.

2.1.2 Methods

Participants

Twenty-five native Japanese speakers were tested in Tokyo, Japan (mean age 24 ± 3.5 ; 13 female). All were students at Keio University, and none had lived abroad.

Stimuli

We constructed a set of 20 base items, 10 disyllabic ones of the form $V_1C_1C_2V_1$ and 10 matched trisyllabic ones of the form $V_1C_1V_1C_2V_1$, with V_1 a vowel in the set /a, e, i, o, u/ (henceforth: flanking vowel), C_1 /h/ or /k/, and C_2 a fixed consonant, /p/, e.g. /ahpa/, /ekpe/, /ohopo/, /ikipi/. Three trained phoneticians, native speakers of Dutch, American English and Argentinian Spanish, respectively, recorded all items with stress on the first syllable. All /kp/ stimuli presented release bursts. For each disyllabic item, we used one token per speaker as a natural control stimulus. By systematically replacing the $/C_1C_2/$ -cluster in these items by the same cluster out of the other disyllabic items produced by the same speaker but with a different vowel, we created spliced test stimuli such as /ah_opa/, and /ek_ipe/, where the small

¹Note that due to a typo the summary in the first-to-last paragraph of this article erroneously states the opposite.

vowel denotes vowel coarticulation present in the consonant cluster. Similarly, by replacing the $/C_1C_2/$ -cluster in the disyllabic items by the same cluster out of the second token of the same items, we created spliced control stimuli in which the vowel coarticulation matched the flanking vowel, e.g. $/ah_a pa/$, $/ek_e pe/$. We also created trisyllabic fillers in which the middle vowel either matched or mismatched the flanking vowel, e.g. $/ahapa/$, $/ekepe/$, $/ahopa/$, $/ekipe/$ (these were also created by splicing, as they served as test stimuli in an experiment not reported in this article). Overall, each speaker thus contributed 40 test stimuli (5 flanking vowels x 4 vowel coarticulations x 2 consonant clusters), 20 control stimuli (5 flanking vowels x 2 consonant clusters, all both in a natural and a spliced form), and 50 fillers. Ten additional training items were recorded by a fourth speaker. Their structure was similar, but included only phonotactically legal nasal + stop sequences with or without an intervening copy vowel (e.g., $/ampa/$, $/enepe/$).

Procedure

Participants were tested individually in a soundproof room. At each trial, they heard a stimulus over headphones and were asked to identify the vowel between the two consonants, if any. They were provided with a transcription of the item on screen, containing a question mark between the two consonants (e.g. “ $ah?pa$ ”) in latin characters (as non-CV syllables cannot be transcribed using Japanese characters), as well as the list of possible responses: “*none, a, i, u, e, o*”. Participants responded by pressing labelled keys on a keyboard. Participants were familiarised with the procedure with 10 training trials in which they received on-screen feedback.

The 330 stimuli were presented in a pseudo-randomised order: Consecutive stimuli were produced by different speakers, and a stimulus could not be followed by a stimulus with the same combination of vowel coarticulation and consonant. Trials were presented in two blocks, with each stimulus appearing once per block, for a total of 660 trials. The experiment lasted approximately 40 minutes.

2.1.3 Results

Test and control trials with responses that were either too fast (before the medial portion of the stimulus could be perceived and processed, <400 ms) or too slow (>3 SD: 3238 ms) were excluded from the analyses. This concerned 736 trials (4.5%).

Control items

Participants experienced perceptual epenthesis in 57% of control items in which the flanking vowel and coarticulation are of the same quality ($/hp/$: 52%, $/kp/$: 61%). Recall that in loanwords, the default epenthetic vowel is $/u/$, while after voiceless laryngeal fricatives it is a copy of the preceding vowel. Focusing on trials with an epenthetic response, we examined whether the choice of epenthetic vowel reflected this pattern.



Figure 2.1: *Percentage of default /u/-epenthesis (left) and vowel copy epenthesis (right) for control items. Box plots display the distribution of the scores across speakers (median, quartiles and extrema), with gray lines connecting data points corresponding to a single participant.*

First, a generalised mixed-effects model with a declared binomial distribution [Bates et al., 2015] was used to examine a possible effect of consonant cluster on default /u/-epenthesis. Thus, we analyzed the proportion of default /u/, using participant, speaker, experimental block, and trial as random effects, and consonant cluster (/kp/ vs. /hp/; contrast coded) as fixed effect. This model was compared to a reduced model with no fixed effect. The full model was found to explain significantly more variance than the reduced model ($\beta = -4.2$, $SE = 1.2$, $\chi^2(1) = 9.9$, $p < 0.01$), showing that participants experienced significantly less default /u/-epenthesis in /hp/- than /kp/-items (39% vs. 86% of all trials with epenthesis, respectively).

Next, we examined whether epenthesized vowels shared the quality of the flanking vowel more often in /hp/- than in /kp/-clusters. Given that for items with flanking vowel /u/ it is impossible to know if /u/-epenthesis is due to vowel copy or to default epenthesis, these items were excluded. As before, a generalised mixed-effects model with a declared binomial distribution was used. We analyzed the proportion of vowel copy (i.e., whether the flanking vowel and epenthetic vowel shared quality), using participant, speaker, experimental block, and trial as random effects, and consonant cluster (/kp/ vs. /hp/; contrast coded) as fixed effect. Comparing this full model to a reduced model with no fixed effects revealed a significant effect of consonant cluster ($\beta = 3.7$, $SE = 1.2$, $\chi^2(1) = 7.4$, $p < 0.01$). Therefore, participants epenthesized a vowel that matched the flanking vowel more often in /hp/-clusters (53%) than in /kp/- clusters (13%).

Thus, analysis of control items revealed that, similarly to the loanword pattern, participants perceived the vowel /u/ more often in /kp/- than in /hp/-clusters, and they perceived a vowel copy more often in /hp/- than in /kp/-clusters.

Test items

Figure 2.2 shows trial counts, separated according to response category, consonant cluster, flanking vowel, and vowel coarticulation for test and control trials. Within

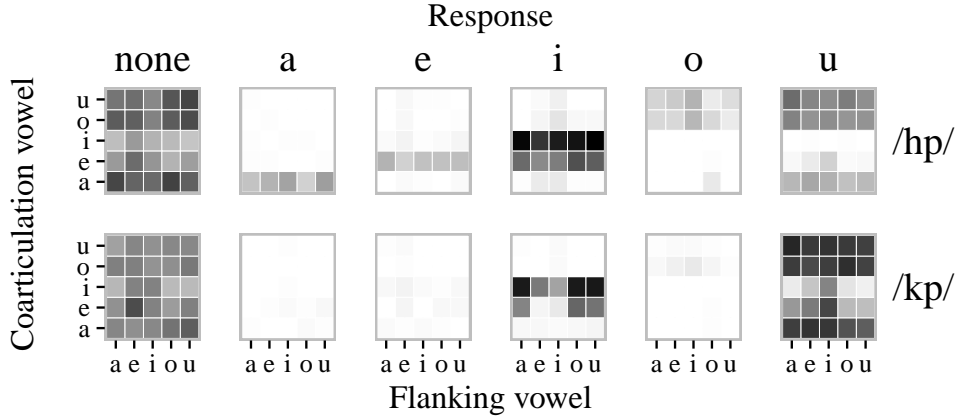


Figure 2.2: *Counts of responses for the test items and spliced control items. Top: /hp/-items; bottom: /kp/-items. Within each rectangle, flanking vowels and vowel coarticulation are given in the horizontal and vertical axes, respectively. Darker colours indicate higher counts. Figure 2.4 shows counts separated by speaker*

the individual rectangles, vertical lines are indicative of a larger influence of flanking vowels compared to vowel coarticulation. Horizontal lines, by contrast, are indicative of a larger influence of vowel coarticulation. Finally, uniform colouring indicates that neither flanking vowels nor vowel coarticulation have the upper hand in influencing the quality of the epenthetic vowel. Note that except for the rectangles with “none” and “u” responses where colouring is more uniform, horizontal lines are more visually prominent than vertical lines. Thus, the epenthetic vowel’s quality generally depends mostly on acoustic details present in the consonant cluster.

Focusing on the test trials eliciting epenthesis (/hp/: 62%, /kp/: 66%), we quantify the respective influence of flanking vowel and vowel coarticulation (explanatory variables, EV) on the epenthetic vowel (response variable, RV), using two measures from information theory, **mutual information** (MI) and **information gain** (IG) [?, see]for a comprehensive description of these measures[daland2015. MI and IG are derived from **entropy**, which is the ‘uncertainty’ in the value of a RV at a given trial. The lower the entropy $H[X]$ of a variable X , the easier it is to predict the outcome of a trial. The **MI** $I[X; Y]$ of variables X and Y represents the reduction in ‘uncertainty’ of the trial outcome for RV X , given that the value of EV Y is known (and vice versa). This corresponds to the maximum amount of influence that Y can have over X , without removing contributions from other variables. **IG** $H[X|Z] - H[X|Y, Z]$ represents the minimum amount of influence of variable Y on X . This corresponds to the reduction in uncertainty as to the value of X that arises from knowing the value of Y , after removing all uncertainty explained by variable Z .

As in [Daland et al., 2015], we compute **accidental information** introduced to MI and IG, which corresponds to inaccuracies introduced to our measurements by the process of inferring underlying probability distributions from samples, i.e., sampling error (as when one does not obtain 50 tails and 50 heads when flipping a fair coin 100 times). We can estimate the accidental information by recomputing MI and IG after having removed the dependencies between the EV and the RV. We can do so by shuffling the values of the EV within each participant. For instance,

in order to compute the accidental information introduced to MI and IG for the EV “vowel coarticulation”, we randomly shuffle the vowel coarticulation labels of all of our trials, per participant, while leaving the EV “flanking vowel” untouched. We then compute MI and IG as for the real data. In order to obtain a better estimate of accidental information from an average value, we do this 1000 times (i.e., Monte Carlo shuffling process).

To recapitulate, for both coarticulation vowel and flanking vowel, we compute ‘sample’ and ‘accidental’ MI and IG. The ‘true’ values of these measures are obtained by removing mean accidental information from sample information. Following [Daland et al., 2015], we consider the set of shuffled datasets (i.e., ‘accidental’ MI and IG) as probability distributions given by the null hypotheses that neither coarticulation nor the flanking vowel influence the responses.

Table 2.1: *Quantified influence of vowel coarticulation and flanking vowel on vowel epenthesis measured with information gain (IG) and mutual information (MI). Ranges for Monte Carlo simulations of the null hypothesis (i.e. accidental information) are given in square brackets. Values are given in bits.*

	Vowel coarticulation				Flanking vowel							
	IG		MI		IG		MI					
	data	null	data	null	data	null	data	null				
/hp/	.90	.04	[.02, .05]	.93	.01	[0, .02]	.07	.03	[.02, .05]	.09	.01	[0, .02]
/kp/	.47	.03	[.02, .05]	.53	.01	[0, .02]	.07	.03	[.02, .04]	.13	.01	[0, .02]

As shown in Table 2.1, all sample lower bounds are greater than their respective accidental information gains on all 1000 shufflings, for which the ranges are given in parentheses. Therefore, the ‘true’ lower bounds for both coarticulation and flanking vowel influence on epenthesis are greater than 0 with $p < 0.001$, showing that both coarticulation and flanking vowel quality influence participant responses. However, the amount of influence differs greatly: a larger information gain is yielded by considering vowel coarticulation than by considering the flanking vowel. This is true both for /hp/-items, which are heavily coarticulated, and for /kp/-items, where coarticulation is mainly only present in the burst, even though the influence of coarticulation on epenthetic vowel quality is higher for the former (/hp/: [0.86, 0.92] *vs.* /kp/: [0.44, 0.52]). (The range of variation within shuffles of accidental information was about .03; thus any difference of .06 or bigger is significant, including differences between MI and IG values, respectively). In summary, both vowel coarticulation and the flanking vowel influence epenthetic vowel quality, but this influence is greater for vowel coarticulation; response patterns are more predictable when the value of this variable is known than when the value of the flanking vowel variable is known.

2.1.4 Discussion and conclusion

We used an identification task to assess the quality of epenthetic vowels perceived by Japanese listeners in illegal consonant clusters with varying amounts of coarticulation. Our findings can be summarized as follows: First, we were able to replicate the perception of illusory vowels within phonotactically illegal clusters by Japanese

listeners (64% of all test trials).²³ Second, when the flanking vowel and coarticulation match, the quality of the perceived vowel patterned in the same way as in loanword adaptation data. That is, for /kp/-clusters, the predominant epenthetic vowel was the standard default vowel for Japanese (/u/), while for /hp/-clusters, it was a copy of the flanking vowel. Finally, and most importantly, in items where the coarticulation and flanking vowel differed, the quality of the epenthetic vowel was significantly influenced by both variables, but the influence of the former was much larger than that of the latter, especially in the case of /hp/. Our discussion focuses on this last finding.

Before discussing its theoretical relevance, let us comment on the numerically small – yet significant – influence of flanking vowel on epenthesis for /hp/-clusters, where vowel coarticulation is maximal. This result suggests a contribution of categorical variables on epenthetic vowel quality (i.e., copy effect). A similar effect, though, was also found for /kp/-clusters, for which loanword adaptation patterns provide no particular reason to propose the existence of a categorical copy phenomenon; indeed, in loanwords, coda-/k/ generally triggers default /u/-epenthesis. Therefore, it is possible that this effect results from a response bias due to task demands: given a perceptually uncertain stimulus, the flanking vowel could prime a ‘copy’ response, for instance, because it was visually available on-screen at each trial (e.g. “ah?pa”). Further work using different tasks is necessary to examine the perceptual reality of this ‘vowel copy’ effect.

Keeping in mind that this work focuses on the choice of epenthetic vowel, while not directly addressing questions related to why phonologically-illegal clusters are repaired, or what the role of phonotactics in epenthesis is, the finding that the quality of the epenthetic vowel is influenced more by coarticulation than by the flanking vowel calls for a perceptual repair mechanism in which acoustic details are taken into consideration. Two-step models in which epenthetic repair is performed after the consonant cluster in the acoustic input has been represented in terms of discrete phonetic categories are therefore ruled out. Rather, like [Dupoux et al., 2011], we argue in favor of one-step models, in which epenthetic vowel quality is based on the similarity between local acoustic cues and prototypical properties of each vowel in the language, such that the closest matching vowel gets selected for insertion. This mechanism can account both for the coarticulation-induced vowel copy effect in items with a /hp/-cluster, as the voiceless glottal fricative /h/ contains strong coarticulation from the adjacent vowels [Keating, 1988] also see Figure 2.3, and for the default /u/-epenthesis effect in items with a /kp/-cluster – which exhibit a lower degree of coarticulation – as /u/ is the phonetically shortest vowel in the language [Han, 1962] and is prone to be devoiced in certain contexts (see footnote).

Focusing on cases where the quality of the epenthetic vowel varies *within language* as a function of the type of cluster, previous studies have investigated whether language-specific phonotactic or phonological properties play a role for the quality

²Note that whereas previous studies examined perceptual epenthesis within clusters with at least one voiced consonant, we presently focused on completely voiceless clusters, a context in which the high vowels /i/ and /u/ may be devoiced in Japanese [Han, 1962, Vance, 1987]

³As pointed out by an anonymous reviewer, the differences in rates of epenthesis by speaker (Dutch: 68%, Am. English: 58%, Arg. Spanish: 66%) are consistent with an important role for acoustic factors in epenthesis, suggesting that participants interpret speakers’ acoustic cues instead of responding based on abstract phonological categories [?, cf.]wilson2014. This can also be seen in more detail when decomposing Figure 2.2 by speaker, as in Figure 2.4

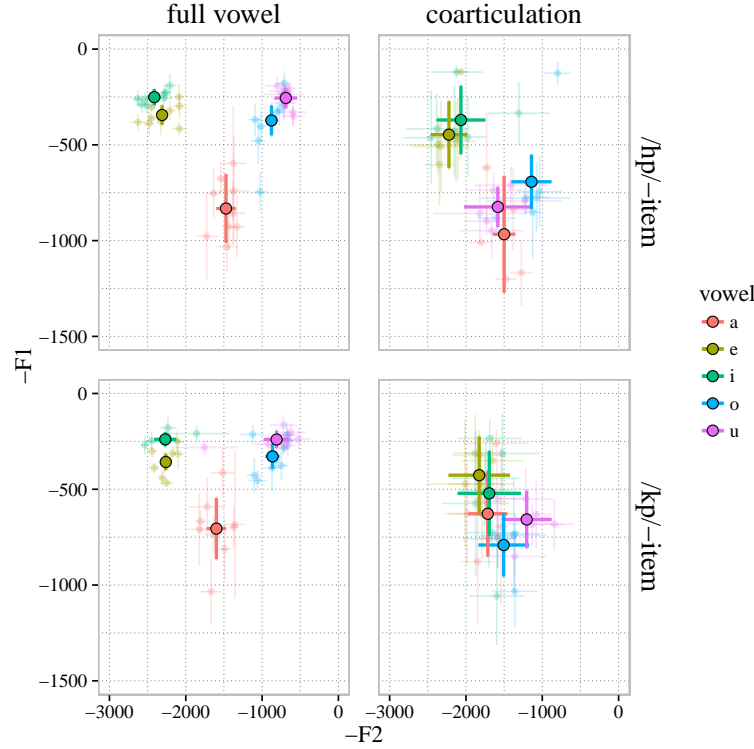


Figure 2.3: *Visualisation in $F1 \times F2$ space of full vowels extracted from CVC portions (left panels), and coarticulation found in the first consonant of CVC clusters (right panels), of items used in the experiment. Dimmer dots and lines respectively show median formant values and median formant bandwidths within the vowel or consonant. Dots circled in black and thicker lines show global means.*

of the epenthetic vowel. In Japanese, for instance, dental stops cannot be followed by /u/, and in loanwords this phonotactic constraint gives rise to adaptation by means of /o/-epenthesis (e.g. 'batman' → 'batoman'). Using identification tasks, both [Mattingley et al., 2015] and [Guevara-Rukoz et al., 2017] report that the perceptual equivalent of this effect is only marginally present in Japanese listeners [?, 10-12% of /o/-epenthesis in /d/-initial clusters; see also]for the absence of such an effect in a discrimination task]monahan2009. Thus, so far there is only weak evidence that the mechanism of phonotactic repair takes into account the legality of the resulting CVC-sequence. A stronger effect of cluster-dependent perceptual epenthesis has been reported in Korean listeners, who repair /ɛjma/ and – to a lesser extent – /ɛ^hma/ with an epenthetic /i/ instead of the default epenthetic vowel /i/ [Durvasula and Kahng, 2015]. This is argued to be due to the existence of an allophonic rule that palatalizes /s/ and /t^h/ before /i/, yielding [ʃi] and [t^hi], respectively. It is also possible, however, that this effect is (partly) due to coarticulation; for instance, acoustic cues in /f/ and /c^h/ might be more suggestive of /i/ than of /i/.

To conclude, we directly compared the relative contributions of acoustic and categorical effects on epenthetic vowel quality, and found that the former override the latter. This result thus strengthens those of [Dupoux et al., 2011], who also established the presence of acoustic effects but without investigating possible categorical

effects. More research is needed to investigate whether our findings generalize to other cases of perceptual epenthesis. This question can be addressed by two complementary approaches. One would be to run additional experiments with cross-spliced stimuli, as in the present study. Another one would be to measure the effective amount of coarticulation in experimental stimuli of previous studies, using a computational implementation of a one-step repair mechanism (see [Dupoux et al., 2011] and [Wilson et al., 2014] for propositions, and [Schatz, 2016] for an implementation using Hidden Markov Models).

2.1.5 Annexes

2.1.6 Supplementary experiment: ABX task

In this additional experiment we assessed the perception of illegal consonantal clusters in Japanese using an ABX discrimination task, which, contrary to the vowel identification task used in Experiment 1, does not require an explicit categorization of the item’s segments. As in previous work [Dupoux et al., 1999, Dupoux et al., 2011], we used different speakers for stimuli A, B, and X, such that the task could not be performed on the basis of low-level acoustic information.

Methods

Participants Twenty-six native Japanese listeners were recruited in Paris, France. While testing for this experiment was done outside of Japan, we recruited only participants with little experience with French or other languages in which consonant clusters are allowed. For instance, many participants were recently arrived exchange students or family members of professionals that had been transferred to Paris.

Stimuli From the stimuli used for the identification task, we extracted items relevant for pairs shown in Table 2.2. We defined four types of AB pairs with constant flanking vowels, based on the nature of the items in the pair:

- Natural cluster items (N) correspond to natural control stimuli from the identification task, disyllabic $V_1C_1C_2V_1$ items which have not been spliced.
- Spliced cluster items (Sp) correspond to the identification task test stimuli, disyllabic $V_1C_1(V_2)C_2V_1$ items for which the $C_1(V_2)C_2$ cluster has been spliced from a $V_2C_1C_2V_2$ item.
- Full vowel items (FV) correspond to trisyllabic fillers from the identification task, $V_1C_1V_2C_2V_1$ items for which the $C_1V_2C_2$ cluster has been spliced from a $V_2C_1V_2C_2V_2$ item.

Procedure Participants were tested in a soundproof room with headphones. On each trial, participants heard two different stimuli of categories A and B, followed by a third stimulus X, belonging either to category A or B. All three stimuli had a $V_1C(V_2)pV_1$ structure, with V_1 and C remaining constant within each trial. All three tokens heard at each trial were produced by different speakers. Stimuli within

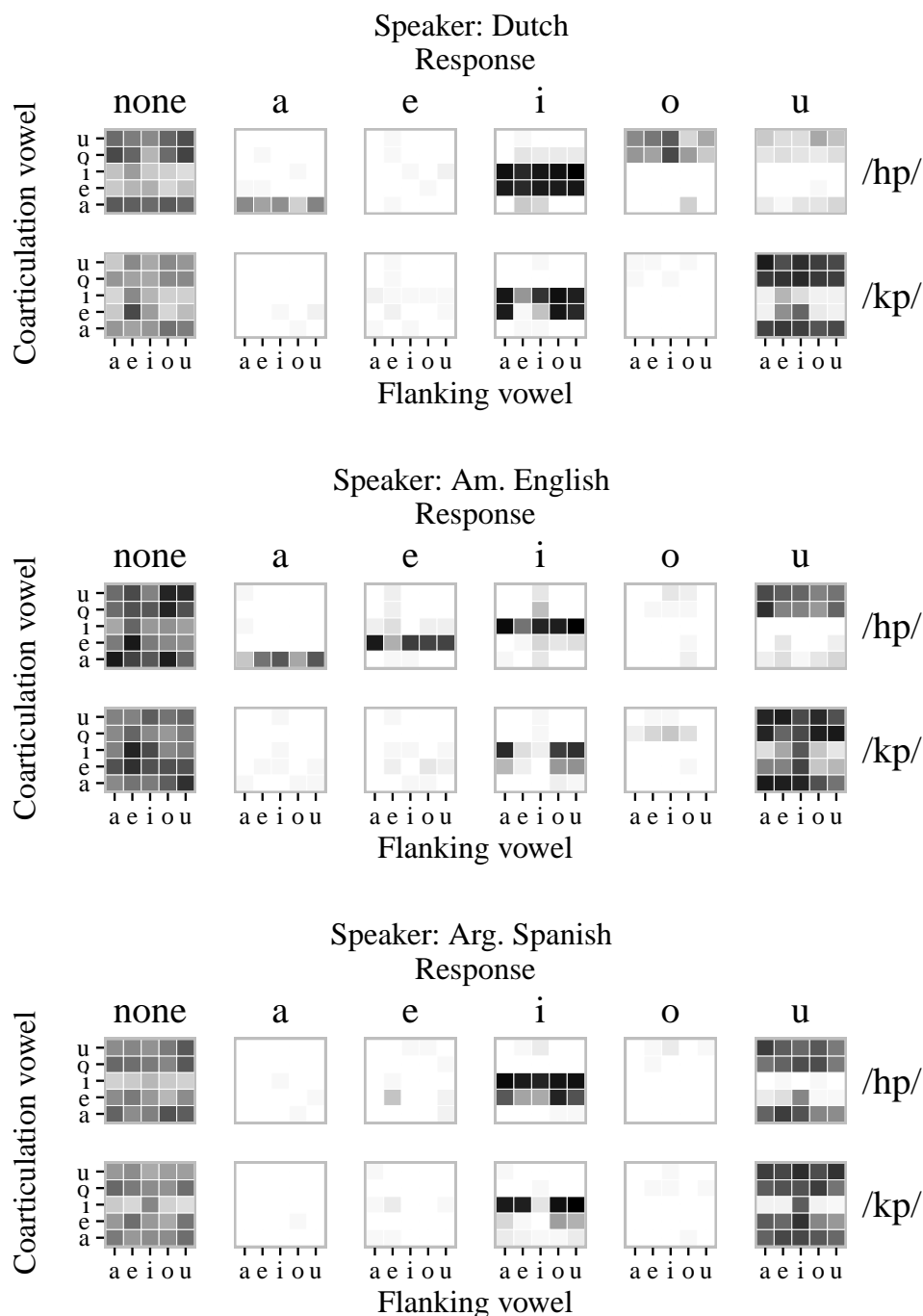


Figure 2.4: *Counts of responses for the test items and spliced control items, separated by speaker. For each speaker: top: /hp/-items; bottom: /kp/-items. Within each individual rectangle, flanking vowels and vowel coarticulation are given in the horizontal and vertical axes, respectively. Darker colours indicate higher counts, with colours normalized within each speaker.*

each trial were presented with an ISI of 500 ms, and an ITI of 1 s separating a participant's response from the following trial.

Within each triplet, A always contained either a natural or a spliced cluster, while B always contained either a full vowel or a spliced cluster. Table ?? shows the

Table 2.2: Types of AB pairs for Experiment 2.

Type	A	B	# pairs	Example
N-FV	natural	full vowel	10	/ahpa/ – /ahapa/
N-Sp	natural	spliced	40	/ahpa/ – /ah _i pa/
Sp-Sp	spliced	spliced	100	/ah _i pa/ – /ah _e pa/
Sp-FV	spliced	full vowel	50	/ah _i pa/ – /ahipa/

four different types of AB pairs that were thus tested.

In total, there were 200 AB pairs. Since there are four possible presentation orders for each pair and its corresponding third item X (i.e., ABX_A , BAX_A , ABX_B , BAX_B), there are 800 possible unique trials. In order to reduce the duration of the experiments, participants were divided into two groups exposed to counterbalanced halves of the total set of trials.

Results

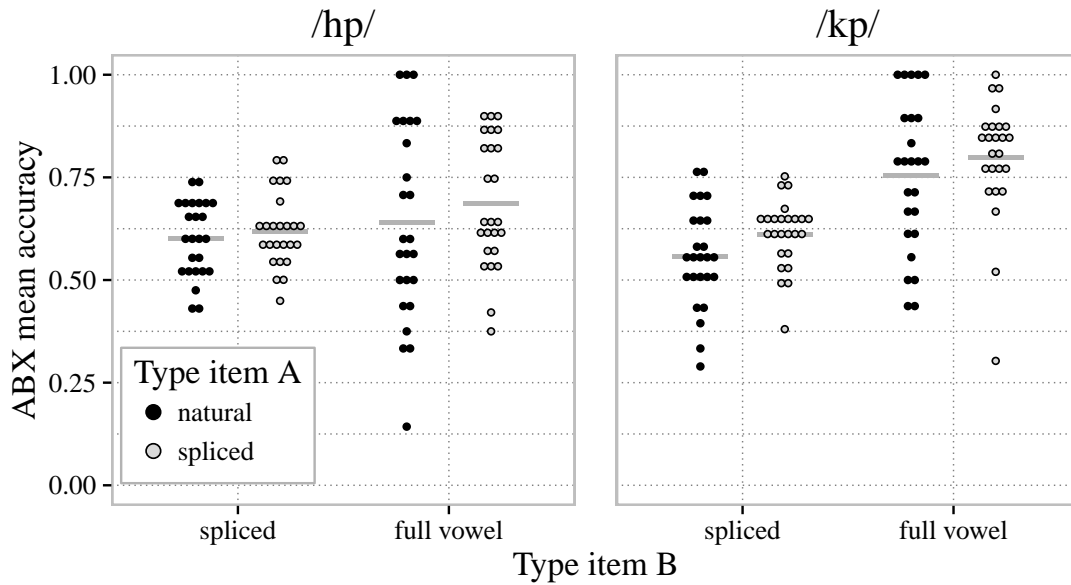


Figure 2.5: *Discrimination accuracy at the ABX task on /hp/ (left) and /kp/ (right) items. Dot plots show the distribution of average scores (one dot per participant). Horizontal grey lines show mean accuracy for each AB pair type.*

Trials in which the response was given before all items in the ABX triplet had been played were excluded (XX trials representing XX%). The remaining data were analysed using a generalised linear mixed-effects model in R (*lme4*; [Bates et al., 2015]) with a declared binary distribution. The binomial response variable of interest for each trial was Accuracy (*correct vs. incorrect*); were included as fixed effects Consonant (/h/ vs. /k/), $Type_A$ (*natural vs. spliced*), $Type_B$ (*full vowel vs. spliced*), as well as the interactions between every pair of fixed effects. All fixed effects were contrast-coded. Participant, $Item_A$, $Item_B$, and Test Group were included as random effects. Significance testing was done through model comparison: the full model

including all fixed and random effects was compared to reduced models, in which one of the fixed effects was absent.

The full model did not explain significantly more data variance than a model excluding the fixed effect Consonant, suggesting that participant accuracy was not significantly different for /hp/ and /kp/ trials ($\beta = 0.17$, $SE = 0.16$, $\chi^2(1) = 1.1$, $p > 0.05$).

We did not find evidence of accuracy being lower or higher when an ABX trial contained a natural cluster item instead of a spliced cluster item ($Type_A$; $\beta = 0.20$, $SE = 0.12$, $\chi^2(1) = 2.52$, $p > 0.05$). Moreover, there was no significant interaction between Consonant and $Type_A$ ($\beta = -0.10$, $SE = 0.17$, $\chi^2(1) = 0.37$, $p > 0.05$), nor between $Type_A$ and $Type_B$ ($\beta = 0.08$, $SE = 0.15$, $\chi^2(1) = 0.26$, $p > 0.05$).

By contrast, accuracy was significantly enhanced by the presence of an item with a full vowel cluster (i.e., *Sp-FV* and *N-FV* pairs) ($Type_B$, $\beta = 0.93$, $SE = 0.16$, $\chi^2(1) = 29.8$, $p < 0.0001$). This increase in accuracy appears to be exacerbated in pairs with /kp/-containing items relative to pairs with /hp/-containing items, as the interaction between Consonant and $Type_B$ was also significant ($\beta = -0.7$, $SE = 0.15$, $\chi^2(1) = 19.0$, $p < 0.0001$).

Correlation between experimental results

In order to assess the role of perceptual assimilation on stimulus discrimination, we derived a measure of perceptual distance from response patterns given in the identification task, and examined if this distance predicted the outcome in the ABX discrimination task. To do so, we computed for each item a six-dimensional numerical vector of the shape $x = [x_1, \dots, x_6]$, with values corresponding to the percent responses to categories a, e, i, o, u, and *none*, respectively. The distance $d(x, y)$ between two items x and y was computed as the normalized Euclidian distance between their associated vectors:

$$d(x, y) = \frac{\sqrt{\sum_i (x_i - y_i)^2}}{\sqrt{2}}$$

One data point was obtained per AB pair, giving a total of 200 datapoints (cf. Table 2.2).

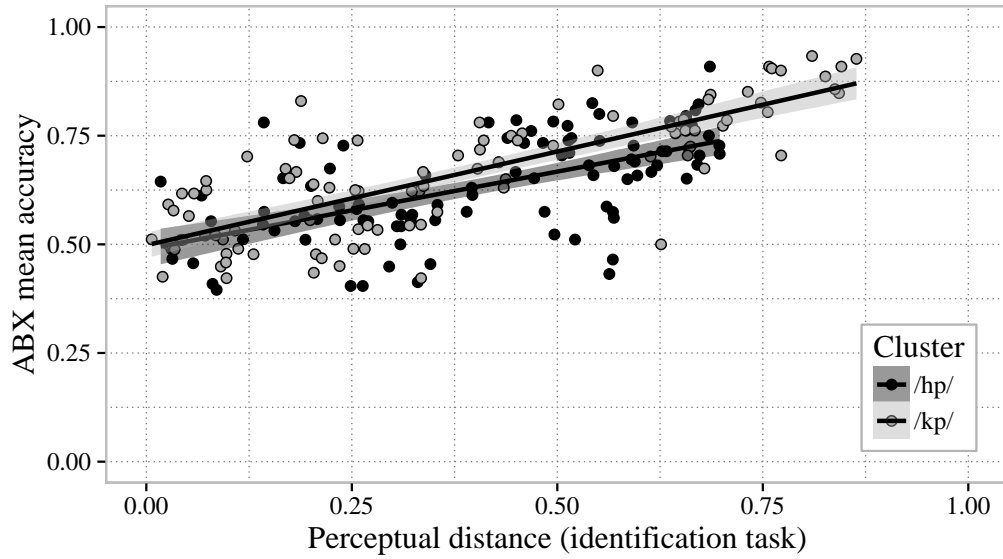


Figure 2.6: *Correlation between the perceptual distance derived from the identification task responses and the accuracy at the ABX discrimination task.*

Multiple regression analysis was used to test if assimilation patterns from the identification task significantly predicted participants' accuracy during the ABX task. A scatterplot summarizes the results in Figure 2.6. The model included as independent variables the normalized perceptual distance between two items (range = $[0;1]$), and the consonant cluster (/hp/ or /kp/). These two predictor variables explained 52% of the variance ($R^2 = 0.52$, $F(3, 196) = 73.63$, $p < 0.0001$). Consonant cluster ($t < 1$) and the interaction of the two independent variables ($t < 1$) were not statistically significant. On the other hand, perceptual distance significantly predicted accuracy during the ABX task ($t = 13.8$, $p < 0.0001$); the less similar the response patterns to both items in the AB pair, the easier their discrimination in the ABX task. These results suggest that adaptation patterns attested in the identification task are not task-dependent.

2.2 Predicting epenthetic vowel quality from acoustics

The following section is a modified version of the following conference proceedings: Guevara-Rukoz, A., Parlato-Oliveira, E., Yu, S., Hirose, Y., Peperkamp, S., and Dupoux, E. (2017). Predicting epenthetic vowel quality from acoustics. Proceedings of Interspeech, 596-600.

Abstract Past research has shown that sound sequences not permitted in our native language may be distorted by our perceptual system. A well-documented example is vowel epenthesis, a phenomenon by which listeners hallucinate non-existent vowels within illegal consonantal sequences. As reported in previous work, this occurs for instance in Japanese (JP) and Brazilian Portuguese (BP), languages for which the ‘default’ epenthetic vowels are /u/ and /i/, respectively. In a perceptual experiment, we corroborate the finding that the quality of this illusory vowel is language-dependent, but also that this default choice can be overridden by coarticulatory information present on the consonant cluster. In a second step, we analyse recordings of JP and BP speakers producing ‘epenthesized’ versions of stimuli from the perceptual task. Results reveal that the default vowel corresponds to the vowel with the most reduced acoustic characteristics and whose formants are acoustically closest to formant transitions present in consonantal clusters. Lastly, we model behavioural responses from the perceptual experiment with an exemplar model using dynamic time warping (DTW)-based similarity measures on MFCCs.

2.2.1 Introduction

When languages borrow words from one another, the borrowed words tend to be adapted to the local phonology. For instance, Brazilian Portuguese phonotactic constraints disallow most obstruent-obstruent and obstruent-nasal sequences, while those of Japanese disallow consonant clusters and consonants in coda position (with the exception of geminates and nasal consonants). Foreign words containing these illegal sequences may be broken up by the insertion of so-called ‘epenthetic’ vowels (e.g., BP: “football” → /futibol/, JP: “ice cream” → /aisukuri:mu/). This phenomenon has been shown to also happen during on-line perception: listeners *perceive* vowels within illegal consonantal sequences [Dupoux et al., 1999, Dehaene-Lambertz et al., 2000, Dupoux et al., 2001, Berent et al., 2007, Kabak and Idsardi, 2007, Monahan et al., 2009, Dupoux et al., 2011, Mattingley et al., 2015, Durvasula and Kahng, 2015]. This suggests that phonotactic constraints of the native language play an active role during speech perception and induce repair of illegal forms such that they are recoded into the nearest legal one. The specific mechanisms of this repair process are still largely unknown. In particular, what determines the quality of the epenthesized vowel? Past work has shown that perceptual epenthesis is language-dependent (e.g., /i/ in BP, /u/ in JP), but also that it may be influenced by local acoustic properties, i.e., by coarticulation [Dupoux et al., 2011]. Here, we study these two effects together, and report, firstly, on a perception experiment with BP and JP listeners. Next, we conduct acoustic analyses of the production of possible epenthetic vowels in a subset of the same participants. Lastly, we present an exemplar-based computational

model of speech perception which attempts to model phonotactic repairs based on acoustics.

2.2.2 Perception experiment

We assess patterns of perceptual epenthesis by BP and JP native listeners on stimuli containing an illegal cluster. We investigate (1) the preferred epenthetic vowel in the two languages (/i/ vs. /u/), and (2) the influence of flanking vowels on responses.

Methods

Fifty-four items with the structure $V_1C_1C_2V_2$, with V_1 and V_2 vowels from the set {/a/, /i/, /u/}, and C_1C_2 a cluster from the set {/bg/, /bn/, /db/, /dg/, /gb/, /gn/}, e.g. /abgi/, were recorded by a native speaker of French. Twenty-two native BP listeners and 17 native JP listeners were tested in São Paulo and Tokyo, respectively. None had extensive exposure to languages that allow complex consonantal clusters. At each trial, participants heard a stimulus and had to indicate within 3 seconds which vowel from the set {/a/, /e/, /i/, /o/, /u/ and *none*} they perceived within the consonant cluster.

Results

Statistical analyses were performed with the R statistical software [R Core Team, 2016], using MCMC glmm [Hadfield, 2010, Plummer et al., 2006]. Effects were considered statistically significant if the 95% highest posterior density (HPD) interval estimated for the variable of interest did not include zero. Please note that we only report effects relevant to hypotheses tested in this work. A full report of all analyses conducted in this section (as well as additional information) can be found in: <https://osf.io/zr88w/>.

In order to assess the influence of V_1 and V_2 (henceforth: flanking vowels) on epenthetic vowel quality (/i/ or /u/), we fitted models with fixed effects Language (BP *vs.* JP), Number of Same Flanking Vowels (NSFV) (*none vs.* 1; *none and 1 vs.* 2) and their interaction, with Participants as random effect. We also included the fixed effect Coronal C_1 (non-coronal *vs.* coronal) and the resulting interactions when analysing /u/ responses, as the insertion of default /u/ after coronal consonants yields phonotactically illegal sequences in Japanese. Fixed effects were contrast coded with deviance coding and, in the case of the trinomial variable NSFVs, comparisons were achieved by creating dummy variables "none *vs.* 1" with weights [-0.5, 0.5, 0] for levels *none*, 1 and 2, respectively, and "Less than 2 *vs.* 2" with weights [-0.25, -0.25, 0.5] for levels *none*, 1 and 2.

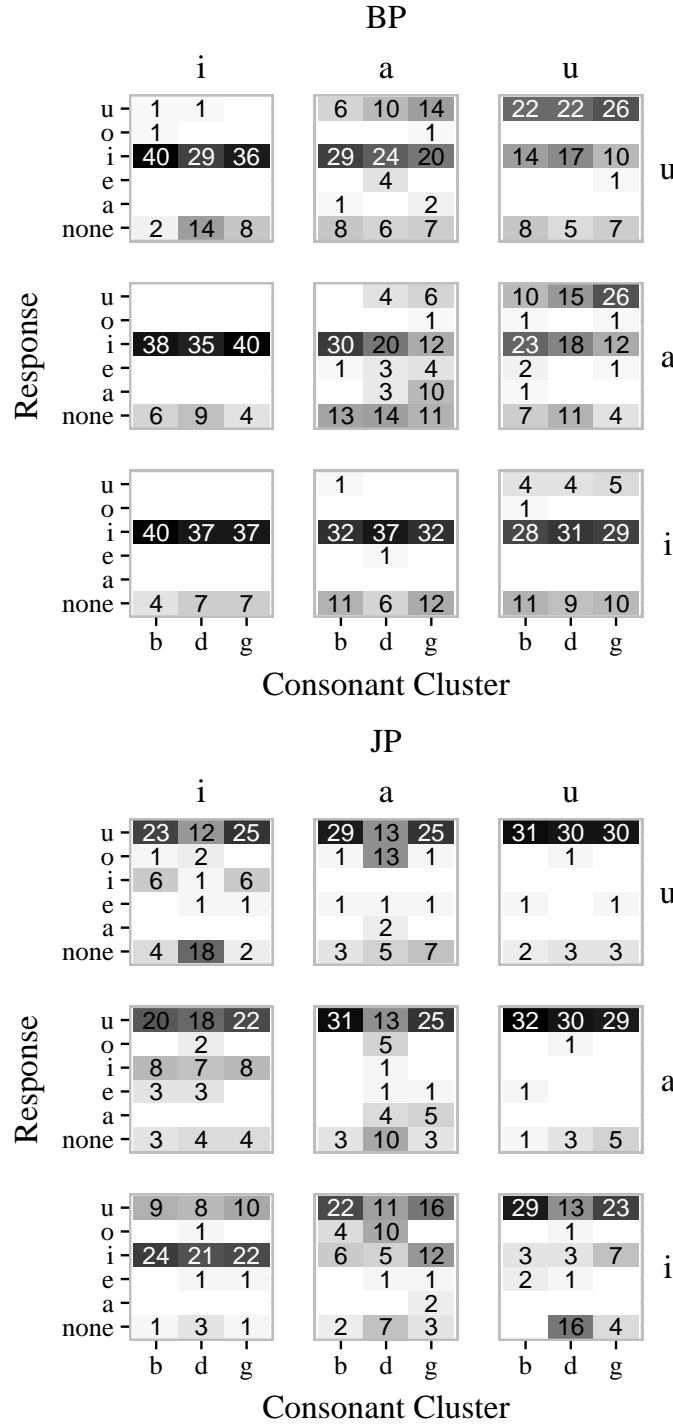


Figure 2.7: Responses for all trials from the perception experiment for both BP (top) and JP (bottom), including trials with responses not given by the exemplar model (“none”, “a”, “e”). Numbers indicate trial counts, with darker cell backgrounds representing higher values. Within each of the two 3 x 3 grid, trials are separated according to V_1 (columns) and V_2 (rows). Within each individual rectangle, the horizontal axis shows the first consonant of the consonant cluster, while the vertical axis corresponds to possible responses.

Response patterns are shown on Figure 2.7. Overall, BP and JP participants experienced vowel epenthesis in 81% and 87% of the trials, respectively. We focus

our analysis on these trials and, in order to allow for comparisons with the model from Section 4 below, we exclude trials for which the reported epenthetic vowel was /a/ (1%) or /e/ (BP: 1%, JP: 3%). Percentages for the remaining responses of interest (/i/, /o/, and /u/) can be seen in the lefthand part of Table 2.3.

Table 2.3: Percentage of responses.

	Human data			Model		
	i	o	u	i	o	u
BP	80.39	0.64	18.97	52.73	6.22	41.05
JP	18.37	5.64	75.98	49.34	0.13	50.52

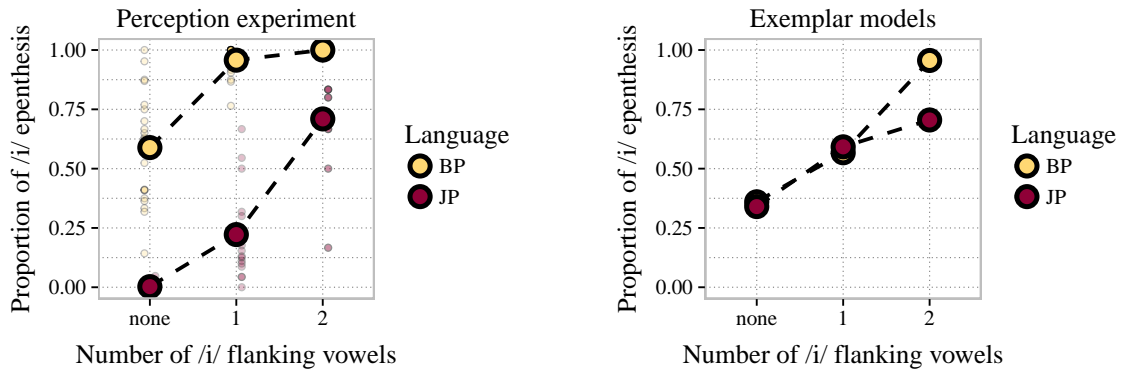


Figure 2.8: *Proportion of /i/-epenthesis in the perception experiment with BP and JP participants (left) and the simulations with the corresponding exemplar-based models (right). Bigger dots show mean values, while smaller dots show individual values for human participants.*

/i/-epenthesis Figure 2.8 shows the proportion of /i/-epenthesis. A main effect of Language shows that BP participants perceived an epenthetic /i/ more often than JP participants (posterior mode: -277.1 , HPD interval: $[-389.2, -167.1]$). Moreover, the propensity to respond /i/ was influenced by flanking vowels, as indicated by a main effect of NSFV: Participants gave more /i/ responses when one flanking vowel was /i/ (204.1 , $[80.8, 283.7]$), and even more so when both flanking vowels were /i/ (368.9 , $[208.4, 443.4]$).

/u/-epenthesis Figure 2.9 shows the proportion of /u/-epenthesis. We found a main effect of Language; BP participants epenthesized /u/ less often than JP participants (265.2 , $[191.0, 347.2]$). The significant main effect of NSFV shows that participants were overall more prone to perceiving an epenthetic /u/ if one (137.0 , $[90.6, 185.4]$) or both (300.3 , $[230.4, 387.7]$) flanking vowels were /u/. Lastly, there was also a main effect of Coronal C_1 (-43.0 , $[-75.8, -9.8]$): participants perceived /u/ less often after coronal than after labial and velar consonants. However, neither the interaction between Coronal C_1 and Language (-63.9 , $[-132.1, 3.0]$), nor the triple interactions with NSFV (-17.8 , $[-124.9, 84.1]$, -14.8 , $[-238.4, 304.3]$) were significant; thus, JP participants were not more prone to avoiding /u/-epenthesis after coronal consonants than BP participants.

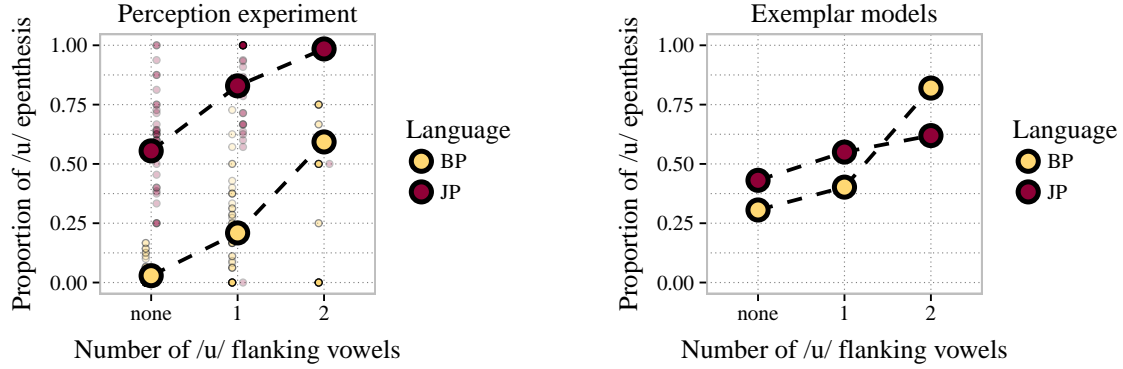


Figure 2.9: *Proportion of /u/-epenthesis in the perception experiment with BP and JP participants (left) and the simulations with the corresponding exemplar-based models (right). Bigger dots show mean values, while smaller dots show individual values for human participants.*

2.2.3 Acoustic analyses

In both BP and JP, the shortest vowel corresponds to the default epenthetic vowel, i.e. /i/ in BP [Escudero et al., 2009] and /u/ in JP [Han, 1962]. Here, we compare epenthetic vowels /i/, /u/, and /o/ on three acoustic parameters: (1) vowel duration, (2) vowel intensity, and (3) Euclidean distance between vowel formants and formant transitions in consonant clusters. We hypothesize that, for both languages, the default vowel is the one (1) that is shortest, (2) that has the lowest intensity, and (3) whose formants are closest to the formant transitions present in consonantal clusters.

Methods

Seventeen BP and 17 JP participants from the perception experiment were also recorded producing 162 stimuli obtained by crossing the 54 $V_1C_1C_2V_2$ frames of the experimental items with the three vowels /i/, /o/, and /u/ (e.g. /ab_gi/ → /abigi/, /abogi/, /abugi/). Items were read aloud in carrier sentences, with stress and pitch accent on the first syllable for BP and JP speakers, respectively. The recordings were manually segmented and transcribed by a trained phonetician. Recordings with errors or unwanted noise were excluded from the analyses. Acoustic measurements were automatically extracted from the speech signal using the R package wrassp [Bombien et al., 2016].

Results

For each of the continuous response variables examined in this section, we fitted an MCMC glmm with fixed effects Language (BP *vs.* JP), Medial Vowel (/i/ *vs.* /u/; /i/ and /u/ *vs.* /o/) and their interaction, with Participant and Item as random effects. Fixed effects were contrast coded with deviance coding and, in the case of the trinomial variable Medial Vowel, the comparisons were achieved by creating a dummy variable "/i/ *vs.* /u/" with weights [-0.5, 0, 0.5] for levels /i/, /o/ and /u/, respectively, and one for "High Vowels *vs.* /o/" with weights [-0.25, 0.5, -0.25]. Multiple pairwise comparisons, using Least Squares Means (LSMEANS) and

Tukey's adjustment, were performed using the R package lsmeans [Lenth, 2016].

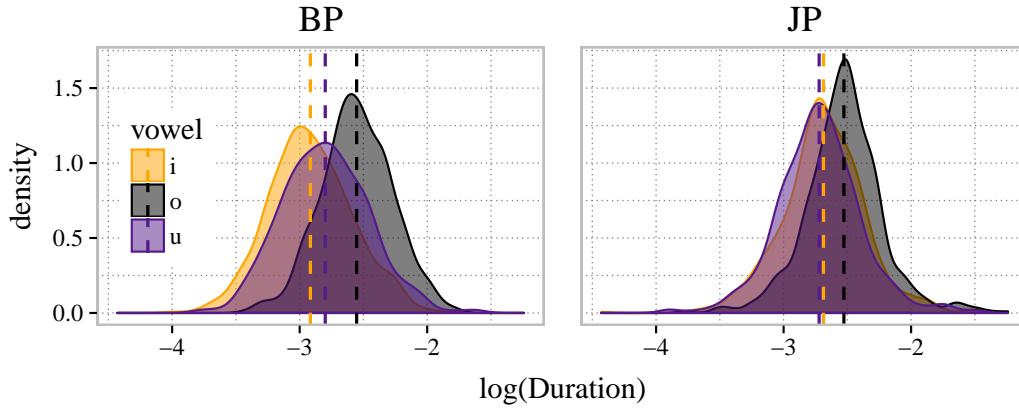


Figure 2.10: *Distribution of log'd vowel duration (in s) of medial vowels /i, o, u/ produced by BP and JP participants. Dashed lines show mean values.*

Vowel duration The measured duration of each medial vowel V_3 (in seconds) was log-transformed to account for distribution skewness. The resulting distributions can be seen in Figure 2.10. We found a main effect of Medial Vowel (" /i/ vs /u/": 0.04, [0.02, 0.06]; "High Vowels vs. /o/": 0.32, [0.30, 0.34]), showing that, overall, /o/ is longer than /u/, which is longer than /i/. The interaction of Language and Medial Vowel was also significant (" /i/ vs /u/": -0.15, [-0.18, -0.10]), reflecting the fact that in BP, /i/ is shorter than /u/ (mean /i/: 57.2 ms; mean /u/: 64.5 ms; adjusted $p < 0.05$) while in JP, /u/ is shorter than /i/ (mean /u/: 69.6 ms; mean /i/: 72.0 ms; adjusted $p < 0.05$).

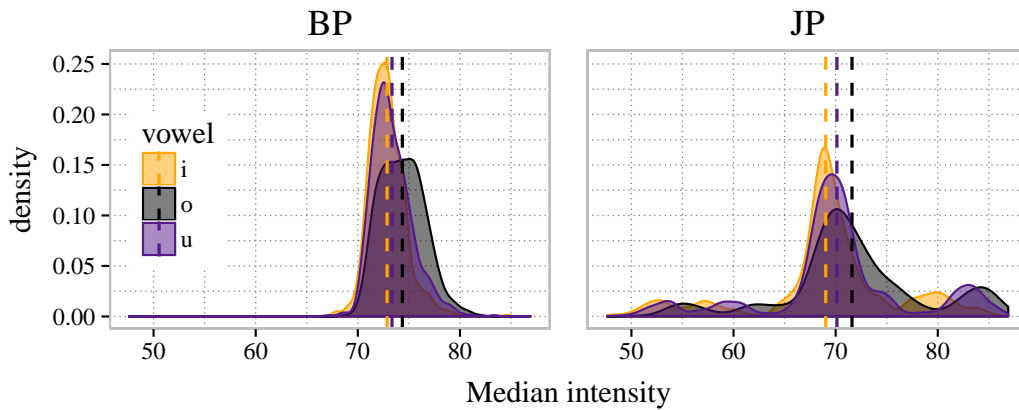


Figure 2.11: *Distribution of median intensity (in dB) of medial vowels /i, o, u/ produced by BP and JP participants. Dashed lines show mean values.*

Vowel intensity We compared the mean intensity of the medial vowels V_3 in decibels (dB). The associated distributions can be seen in Figure 2.11. There was a main effect of Medial Vowel, with /i/ having on average lower intensity than /u/ (0.8, [0.7, 1.1]), and high vowels having lower intensity than /o/ (2.1, [1.9, 2.4]). Of

interest is the fact that the former effect is larger for JP than for BP (Language \times "/i/ vs /u/": 0.38, [0.09, 0.90]), meaning that while /i/ is the vowel with least intensity in BP (mean: 72.8 dB vs. 73.2 for /u/; adjusted $p < 0.05$), the reverse is not true for JP (mean: 69.7 dB for /u/ vs. 68.7 for /i/, adjusted $p < 0.05$). This might be due to an overall higher degree of vocal constriction during the production of /i/ compared to /u/.

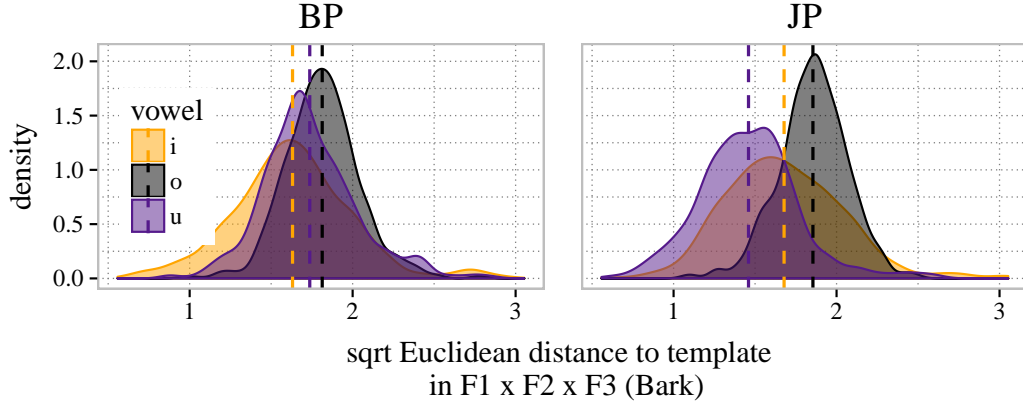


Figure 2.12: *Distribution of square root Euclidean distance to template in F1 x F2 x F3 space (frequencies in Bark) of medial vowels /i/, o, u/ produced by BP and JP participants. Dashed lines show mean values.*

Vowel formants We extracted median formant values (F1, F2, and F3, in Bark) from medial vowels V_3 and computed their Euclidean distance to the transitions found within their respective clusters (e.g. the /i/ in /abiga/ was compared to transitions in /bg/ from the French recording of /abga/). The resulting distributions can be seen in Figure 2.12. These Euclidean distances were square-root transformed to account for skewness. There was a main effect of Medial Vowel, as on average distance was shorter for /u/ than for /i/ (-0.06 , $[-0.08, -0.04]$), while it was longer for /o/ relative to both /i/ and /u/ (0.28 , $[0.25, 0.30]$). Of interest is the significant interaction between Language and Medial Vowel "/i/ vs /u/" (-0.31 , $[-0.36, -0.28]$), reflecting the fact that in BP /i/ formants were closer to cluster transitions than /u/ formants (mean: /i/ 2.8 vs. /u/ 3.1, adjusted $p < 0.05$), while the reverse held in JP (mean: /i/ 2.9 vs. /u/ 2.2, adjusted $p < 0.05$).

2.2.4 Production-based exemplar model

We built an exemplar model of the perception of phonotactically illegal consonant clusters by BP and JP listeners, exclusively based on acoustics. We used all participants' productions from Section 3 as the inventory of exemplars available to our model. This is a simple way of representing the acoustics that a BP/JP native listener may have been exposed to during language development. As an analogy to the perception experiment from Section 2, the model classified each $V_1C_1C_2V_2$ template as $V_1C_1iC_2V_2$, $V_1C_1oC_2V_2$, or $V_1C_1uC_2V_2$, based on the similarity of the template to exemplars of these three categories available in the inventory. We examined whether the model was able to predict participants' epenthetic patterns, in

particular, whether it was able to mimic preferences for default vowels and capture the modulation of these preferences induced by flanking vowels.

Methods

Recordings from Section 3 were converted into sequences of 39-dimensional feature vectors consisting of 12 Mel-frequency cepstral coefficients (MFCCs) and energy features⁴, with delta and delta-delta coefficients. Coefficient values were standardised. We computed the optimal alignment between all $V_1C_1C_2V_2$ templates (e.g. /abgi/) and their corresponding $V_1C_1V_3C_2V_2$ epenthesized versions (e.g. /abigi/, /abogi/, /abugi/) using Dynamic Time Warping (DTW) [Sakoe and Chiba, 1978, Giorgino, 2009]. In order to ensure that the resulting distances were not mainly influenced by spectral differences of flanking vowels V_1 and V_3 , we only compared C_1C_2 clusters to $C_1V_3C_2$ sections. Note, however, that coarticulation cues from flanking vowels are expected to be present within the clusters.

For the simulation, we built a classifier that assigns any given template to one category in the set $\{V_1C_1iC_2V_2, V_1C_1oC_2V_2, V_1C_1uC_2V_2\}$, based on acoustic similarity. Similarity s between templates and epenthesized versions was defined as

$$s = e^{-cd} \quad (2.1)$$

where d is the DTW distance, and c is a parameter determining the weight of the DTW distance on classification [Nosofsky, 1992]. When $c = 0$, DTW is disregarded and all possible classification categories are equally probable. Higher values of c result in higher probabilities being given to items with smaller d . In order to control for unequal number of tokens in each category, classification was performed by computing the mean similarity within each category. From there we sampled a classification label weighting category probabilities by the resulting mean similarity weights. Parameter c was individually optimised for each language by performing leave-one-out cross-validation (maximum accuracy: 0.50 with $c = 0.5$ for BP, and 0.63 with $c = 2.2$ for JP; chance level at 0.33).

Results

The same statistical models from Section 2, but without a random effect for Participant, were used.

The perception model was able to accurately predict participant responses for 59.1% (BP) and 58.4% (JP) of trials. Figure 2.14 shows a detailed distribution of the responses. As shown in the righthand part of Table 2.3, the model rarely predicted /o/ responses, as expected based on acoustic analyses; however, it is surprising that most /o/ responses were predicted for BP rather than for JP. This might be due to overlap of /u/ and /o/ in the formant space of BP, which is visible in Figure 2.13.

Concerning /i/ and /u/, numerically the model predicted more /i/ responses than /u/ responses for BP, and the opposite for JP. However, these differences are not as clear as they are for our human data, where in both languages the default vowel is chosen four times more often than the non-default high vowel.

⁴Due to a mistake in the feature computation pipeline, this meant that the log energy and the 12 first MFC coefficients were concatenated, not that the first coefficient of 13 coefficients was replaced by the log energy, as was originally intended.

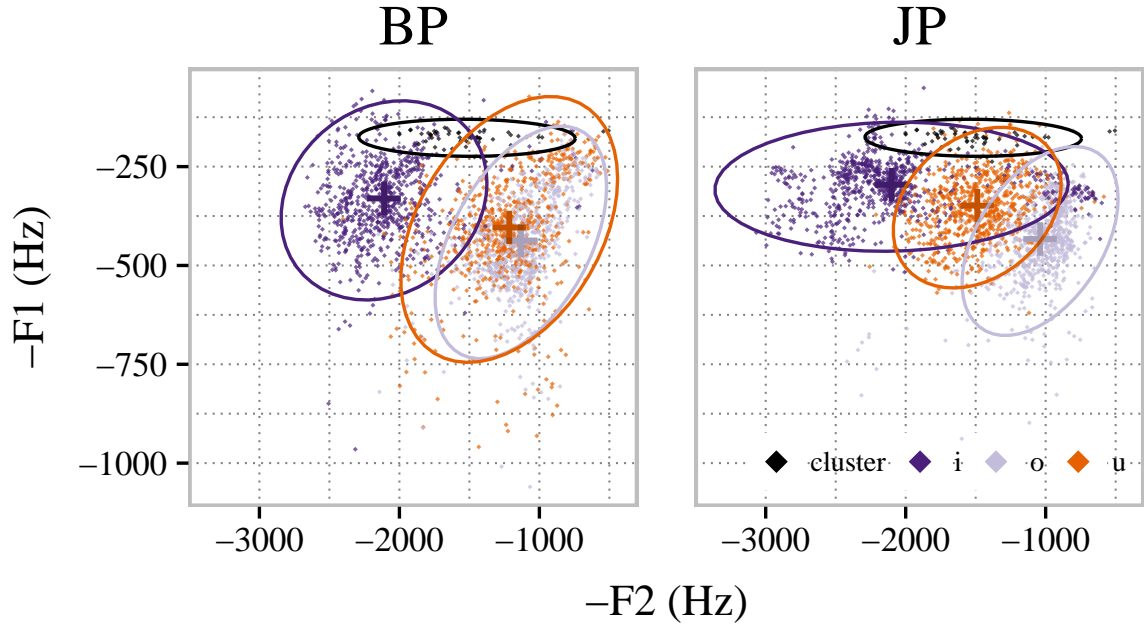


Figure 2.13: *Medial vowels and clusters in F1 x F2 space.*

/i/-epenthesis Figure 2.8 shows the proportion of /i/-epenthesis for human participants and the corresponding exemplar models. We found a main effect of Language (-52.0 , $[-86.9, -23.8]$) and a main effect of NSFV (*none* vs. 1: 93.3 , $[53.0, 125.0]$; Less than 2 vs. 2: 245.7 , $[150.8, 328.2]$). Thus, our model is able to reflect the higher frequency of /i/ as epenthetic vowel in BP compared to JP participants, as well as the influence of flanking vowels on /i/-epenthesis in both BP and JP.

/u/-epenthesis Figure 2.9 shows the proportion of /u/-epenthesis for human participants and the corresponding exemplar models. We found a main effect of NSFV (*none* vs. 1: 37.8 , $[16.0, 62.3]$; Less than 2 vs. 2: 190.7 , $[131.0, 240.6]$) but not of Language (-15.9 , $[-50.2, 10.1]$). Thus, while our model was able to qualitatively reproduce the influence of flanking vowels on epenthetic vowel quality for /u/, it was unable to reflect the fact that JP listeners perceive /u/ more often than BP listeners.

There was also a main effect for Coronal C_1 (-66.7 , $[-95.6, -39.5]$) but no interaction of this effect with Language (40.2 , $[-28.0, 91.8]$); similarly to the perception data, this reflects an overall lower propensity for the model to ‘epenthesize’ /u/ after coronal consonants. The triple interaction NSFV x Coronal C_1 x Language was significant for both “levels” of NSFV (94.1 , $[19.9, 210.6]$, 525.8 , $[275.5, 666.1]$). Closer inspection suggests that this reflected the model’s inability to predict higher percentages of /u/-responses by both BP and JP participants after coronal consonants when both flanking vowels were /u/.

2.2.5 Discussion

Examining epenthetic vowel quality preferences by BP and JP speakers in a perception task, we corroborated previous findings ([Dupoux et al., 1999, Dupoux et al., 2011])



Figure 2.14: Responses from the perception experiment (left) and model predictions (right), for both BP (top) and JP (bottom), on trials common to the human and model experiments. Numbers indicate trial counts, with darker cell backgrounds representing higher values. Within each 3 x 3 grid, trials are separated according to V_1 (columns) and V_2 (rows). Within each individual rectangle, the horizontal axis relates to whether C_1 is coronal (/d/) or not, while the vertical axis corresponds to possible responses. For instance, BP participants experienced /i/-epenthesis in all 78 trials involving /iC₁C₂a/ stimuli for which C_1 was not the coronal consonant /d/.

that, like in loanword adaptations, the default epenthetic vowel during speech perception is /i/ for BP and /u/ for JP. Our acoustic analyses suggest that the choice of epenthetic vowel is acoustically driven. That is, in BP, /i/ is shorter and spectrally closer to the formant transitions in our stimuli than /u/ (and /o/), while the reverse holds in Japanese. As such, it may not be necessary to rely on phonological explanations of epenthetic vowel quality as in [Rose and Demuth, 2006, Uffmann, 2006], were we to find that these are shared characteristics of default epenthetic vowels in a variety of languages. We also found an influence of flanking vowels on epenthetic vowel quality, similar to what was reported in [Dupoux et al., 2011]. Indeed, participants gave fewer default responses when the quality of the flanking vowels was in disagreement with the default choice, resulting in more “vowel copy” epenthesis (i.e. perceiving a vowel of the same quality as that of a flanking vowel). Furthermore, we found that this effect of flanking vowels is additive, as it is even more prominent when both flanking vowels are of the same quality.

Interestingly, phonotactics did not influence JP participants’ responses as may

have been expected; while /o/ was almost exclusively perceived after coronal consonants, this was almost always the case for stimuli with $V_1 = /a/$ (cf Figure ??). In fact, for all combinations of flanking vowels, participants responded /i/ and/or /u/ more often than /o/ in coronal contexts, even though both /du/ and /di/ are phonotactically illegal sequences in JP. These results, which are reminiscent of previous work [Monahan et al., 2009, Mattingley et al., 2015], suggest that constraints on perception given by surface phonotactics can be overruled by constraints relative to matching input acoustics [Dupoux et al., 2011]. In fact, if this were not the case, novel sound sequences would have never arisen in JP loanwords (e.g. *party* is adapted as /pa:ti/, not /pa:tɕi/).

Finally, we presented results from one exemplar model per language, based on productions by BP and JP participants, respectively. These models reproduced the major effects found in the perception experiment — namely, the preferred epenthetic vowel (numerically), and some significant effects of language and flanking vowels — although with a high level of noise. This noise level may be due to the relatively low number of tokens that were available as exemplars, the fact that the DTW procedure removes temporal cues (recall that we found that default vowels tend to be of shorter duration), and/or the fact that MFCC features do not appropriately capture speaker invariance. We interpret the results as providing a proof of principle that some of the salient effects regarding perceptual epenthesis can be accounted for on purely acoustic grounds. Future research is needed to improve on the model, whose predictions deviated from the perceptual data on several counts (e.g., 6% /o/-epenthesis for BP, but less than 1% for JP; failure to produce more /u/-epenthesis for JP than BP). These improvements could involve more phonetically and/or temporally informed features (e.g., spectrotemporal representations [Chi et al., 2005]), state-of-the art large-scale approaches with HMM or DNN systems, or physiologically-inspired models of speech perception (e.g., based on cortical oscillations [Hyafil et al., 2015]).

To conclude, a triple approach combining perception experiments, acoustic analyses, and modeling allows us to gain insight into the mechanisms underlying perceptual epenthesis, and, more generally, repairs of illegal phonological structure during speech perception.

2.3 Predicting epenthetic vowel quality from acoustics II: It’s about time!

2.3.1 Introduction

2.3.2 Methods

Features

In order to ensure feature compatibility with future experiments (due to differences in file formats), features were recalculated using the Kaldi speech recognition toolkit [Povey et al., 2011], introducing slight changes regarding the parameters used in section 2.2. As in section 2.2, audio recordings of items used as stimuli in the perceptual experiment and those used for the acoustic analyses were converted into sequences of 39-dimensional feature vectors consisting of 13 Mel-frequency cepstral coefficients (MFCCs), with delta and delta-delta coefficients. In contrast to our previously used features, here our first coefficient did not correspond to the log of the total frame energy, but to the zeroth cepstral coefficient. We applied this change purely due to the change in the tools used for computing the features. Since the zeroth coefficient corresponds to the sum of the log of the 40 mel values, it is roughly equivalent to the log energy. Additionally, we added 3 coefficients (and their corresponding delta and delta-delta coefficients) adding pitch information to our features: normalized-pitch, delta-pitch, voicing-feature. The final 48 coefficient values were standardised to each have zero-mean and unit-variance. The final 48 coefficient values were standardised to each have zero-mean and unit-variance within each speaker.

Classification

For the simulation, we built a classifier that assigns any given template to one category in the set $\{V_1C_1iC_2V_2, V_1C_1oC_2V_2, V_1C_1uC_2V_2\}$, based on acoustic similarity to the exemplars recorded by native speakers of BP and JP.

Dynamic Time Warping As in section 2.2, we computed the optimal alignment between all $V_1C_1C_2V_2$ templates (e.g. /abgi/) and their corresponding $V_1C_1V_3C_2V_2$ epenthesized versions (e.g. /abigi/, /abogi/, /abugi/) using Dynamic Time Warping (DTW) [Sakoe and Chiba, 1978] with the R package *dtw* [Giorgino, 2009]. In order to ensure that the resulting distances were not mainly influenced by spectral differences of flanking vowels V_1 and V_3 , we only compared feature frames corresponding to C_1C_2 clusters and $C_1V_3C_2$ sections. Note, however, that coarticulation cues from flanking vowels are expected to be present within the clusters.

Concerning DTW specifics, in section 2.2 we used the commonly used step pattern for which, at position $x_{i,j}$, the only possible steps are towards positions $x_{i+1,j}$ (horizontal step), $x_{i,j+1}$ (vertical step), or $x_{i+1,j+1}$ (diagonal step). In this default setting (named “symmetric2” in the R package *dtw*), a diagonal step is twice as costly as a horizontal or vertical step, which favours template-query matches with compressions/stretching over more direct matches. Therefore, in this section we chose to opt for a step pattern with the same three possible steps as before (i.e., horizontal, vertical, diagonal), but for which diagonal steps cost as much as

horizontal/vertical steps on the final DTW distance. Since distances obtained with this step pattern (“symmetric1”) cannot be normalised by being divided by the sum of the lengths of the template and query, we normalise by dividing the cumulative distance by the length of the optimal path.

From the DTW we extract two values per template-query combination: (1) DTW_{dist} , the normalised DTW distance between the template and the query, and (2) DTW_{time} , the proportion of non-diagonal steps taken in the optimal path. This latter value, which was not present in the previous version of the model, is an indicator of the proportion of time dilation and time compression that was required to match the template and the query.

Similarity function We reprise the similarity function used in section 2.2, inspired by the exemplar-based generalized context model (GCM) detailed by [Nosofsky, 1992], and make modifications to accommodate for the inclusion of the duration mismatch penalty DTW_{time} . Our goal is to classify the $V_1C_1C_2V_2$ template into a category from the set of vowels /i, o, u/, through the similarity of the template to exemplars $V_1C_1iC_2V_2$, $V_1C_1oC_2V_2$, and $V_1C_1uC_2V_2$, respectively. We obtain $P(R_J|S_i)$, the evidence favouring category J given stimulus i , by averaging the similarity of said stimulus i to all recorded exemplars of category J . Since we do not aim to introduce a language model to the exemplar model, as we want it to be based entirely on acoustics, we do not introduce a term for response bias for category J . All exemplars are weighted equally.

$$P(R_J|S_i) = \frac{\frac{1}{n_J} \sum_{j \in C_J} \eta_{ij}}{\sum_K \frac{1}{n_K} \sum_{k \in C_K} \eta_{ik}} \quad (2.2)$$

where n_J is the number of exemplars of category J and with η defined as in equation 2.3,

$$\eta_{ij} = e^{-c \cdot d_{ij}} \quad (2.3)$$

where c is a parameter determining the weight of η_{ij} on classification. When $c = 0$, DTW is disregarded and all possible classification categories are equally probable. Higher values of c result in higher sampling probabilities being given to items with smaller distance η_{ij} .

η_{ij} is defined as in equation 2.4

$$\eta_{ij} = w_{dist} \cdot DTW_{dist} + w_{time} \cdot DTW_{time} \quad (2.4)$$

where w_{dist} and w_{time} are weights given to DTW_{dist} and DTW_{time} , respectively. Setting $w_{time} = 0$ gives an equivalent equation to the one used in section 2.2.

Parameter estimation

We used grid search in order to optimise parameters c with $w_{dist} = 1$, for each language. We classified all exemplars to a category within /i, o, u/ in a leave-one-out method. Namely, we assessed the accuracy in the classification of tokens with known labels, by measuring their respective similarity to all other exemplars and sampling the classification categories for each. We assessed the optimality of parameter combinations based not only on mean classification accuracy, but on median

classification accuracy. Indeed, as can be seen in figure 2.15, these two measures are positively correlated but an increased performance at the level of median accuracy might not be obvious when inspecting mean accuracy.

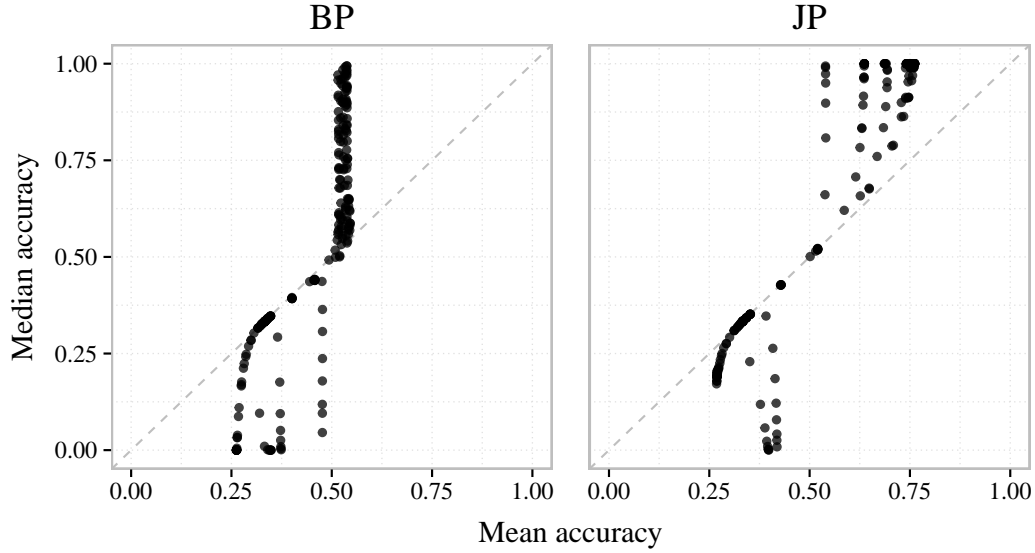


Figure 2.15:

Data analysis

Statistical analyses were performed with the R statistical software [R Core Team, 2016], using Markov chain Monte Carlo generalised linear mixed-models [Hadfield, 2010, Plummer et al., 2006]. These Bayesian models sample coefficients from the posterior probability distribution conditioned on the data and given priors. We used priors that are standard for mixed-effects multinomial models. Model convergence was assessed by visual inspection of trace plots and the Gelman–Rubin convergence diagnostic [Gelman and Rubin, 1992], using four chains with different initialisations. Effects were considered statistically significant if the 95% highest posterior density (HPD) interval estimated for the coefficient of interest did not include zero.

In order to assess the influence of V_1 and V_2 (henceforth: flanking vowels) on epenthetic vowel quality (/i/ or /u/), we chose as fixed effects for our models LANGUAGE (BP *vs.* JP, sum contrast coded) and NUMBER OF SAME FLANKING VOWELS (NSFV; considered as a continuous variable with values 0, 1, or 2 instead of a factor with 3 levels, in order to reduce the number of model parameters and promote convergence), as well as their interaction. As random effects we included CLUSTER and PARTICIPANT when analysing data from the perceptual experiment, and CLUSTER when analysing data from the exemplar models. We also added random slopes for LANGUAGE on CLUSTER, and NSFV on PARTICIPANT. Please note that we re-analyse data from the perceptual experiment described in section 2.2 because the statistical models used for the analyses in this section are not identical to those used in section 2.2. The change in models was motivated by a will to avoid coefficient inflation due to the sparsity of our data, as it was the case in section 2.2.

2.3.3 Results

2.3.4 Discussion

2.4 Summary and Discussion

Similarly to what has been previously observed [Dupoux et al., 1999, Dehaene-Lambertz et al., 2000, Dupoux et al., 2011, Monahan et al., 2009, Mattingley et al., 2015][CITE], I find that BP and JP participants experience perceptual vowel epenthesis when presented auditory stimuli with illegal consonant clusters. For most cases, BP and JP participants insert what has been called a “default” epenthetic vowel, namely /i/ and /u/, respectively. Confirming intuitions laid out by [Dupoux et al., 2011] and reminiscent of the **P-map theory** in [Steriade, 2001], acoustic measurements revealed that these vowels were, within their respective languages, acoustically minimal in that they were of shorter duration and closer in formant space to cluster transitions than other candidate vowels.

Also in agreement with previous observations [Dupoux et al., 2011], I find that the quality of epenthetic vowel is modulated by the identity of flanking vowels: In **section 2.2**, we see more /u/-epenthesis by BP participants with more /u/ flanking vowels, and more /i/-epenthesis by JP participants with more /i/ flanking vowels. Were these modulations of epenthetic vowel quality due to coarticulation cues contained in the consonant clusters or were they due to a phenomenon of vowel copy?

This question was tackled in **section 2.1**, by assessing the perception of stimuli for which the identity of the flanking vowels was in disagreement with that of the coarticulation cues contained within consonant clusters. It was found that, while both flanking vowel and coarticulation influenced epenthetic vowel quality, it was the latter that was the most determinant. This is reflected by the results of the exemplar models evaluated in **section 2.2**. Indeed, these models compared the acoustics of non-native *CC* clusters to native *CVC* exemplars, in order to determine the quality of the vowel to be epenthesized. And while they were unable to mimic default vowel epenthesis, they were able to reproduce quality modulations due to neighbouring vowels. Yet, these models could not perform vowel copy in a way other than by exploiting coarticulation remnants within the clusters.

Concerning the models’ failure to reproduce language-specific default epenthetic vowels, it is difficult to derive the conclusion that acoustics do not have a role in determining default epenthetic vowel quality. Indeed, as previously stated, our proof of concept exemplar model is very limited, as it performs pure acoustic matching between queries and a template without taking (vowel) duration into consideration, and lacking any sort of speaker normalisation.

Adding to these concerns, it is important to add that the model supposes the existence of **multi-phonemic** exemplars to which the non-native input is compared to. Leaving aside the fact that the use of exemplar representations during speech perception may be controversial, an important side-effect of exemplar-based models is that they are unable to model lack of epenthesis. Yet we saw in both **sections 2.1 and 2.2** that participants did choose the “no epenthesis” options in **several instances**.

As such, we will now focus on perception models that are flexible enough to also output illegal structures, as our participants do. And, most importantly, the

following models shall evaluate epenthetic vowel quality without ignoring the role of phonology (e.g., phonotactics) on misperception of non-native clusters. They must therefore incorporate statistics relative to the frequencies of phonemes and their structural arrangements.

As discussed in section 2.1, ours and [Dupoux et al., 2011] results are better aligned with one-step theories of non-native speech perception than with two-step theories. Indeed, the influence of acoustic details on epenthetic vowel quality would be lost if epenthesis occurred after an initial categorisation step; computation of the optimal output must incorporate acoustics and phonotactics in a unique step. In the following sections we will be switching from a one-step DTW-based exemplar model of non-native speech perception to more elaborate one-step Hidden Markov Models (HMM) that do not have the limitations listed above.

Chapter 3

Chapter Three Title

3.1 General methods

3.1.1 ASR tools as models of perception

3.1.2 Dissecting the model

Corpora

CSJ

- General description (type of speech, number of speakers)
- Alignment?
- Phone set
- ...

KCSS

- General description (type of speech, number of speakers)
- Alignment?
- Phone set
- ...

Features

- What are MFCCs
- VTLN and CMVN
- Pitch
- LDA?
- ...

Acoustic model

- Monophone model - also, why?
- Number of gaussians
- Number of states
- ...

Language models

- WFSTs
- Words & phones
- n-grams
- ...

Decoding

- Lattice generation
- Acoustic and LM scores
- nbest
- CTM
- ...

3.1.3 Assessing native performance

Lexicon-based decoding

Phonetic-based decoding

3.1.4 Human-model comparisons

Simulations

Data analysis: ABC easy as 123

Reasoning

Model selection

Parameter tuning

3.2 Parlato2 - duration

3.2.1 Introduction

3.2.2 Methods

Stimuli

We used the same stimuli as in section 2.2. As a reminder, a native French speaker recorded 54 items with the structure $V_1C_1C_2V_2$, with V_1 and V_2 vowels from the set $\{/a/, /i/, /u/\}$, and C_1C_2 a cluster from the set $\{/bg/, /bn/, /db/, /dg/, /gb/, /gn/\}$ (e.g. /abgi/).

Language models

In order for the decoding task to be analogous to the experiment described in section 2.2.2, trial-specific language models were constructed, as shown in Figure 3.1. Thus, when decoding a $V_1C_1C_2V_2$ stimulus, the perception model is only given the possibility to transcribe it as $V_1C_1(V_3)(SIL)C_2V_2$, where phones between parentheses are optional and V_3 is from the set $/a, e, i, o, u/$. In this section our language model is only used to constrain the list of possible outputs from decoding; one output is not more probable than another based on the language models alone. Therefore, here we use a null language model, meaning that the quality of the epenthized vowels will only be determined by acoustic and duration matches.

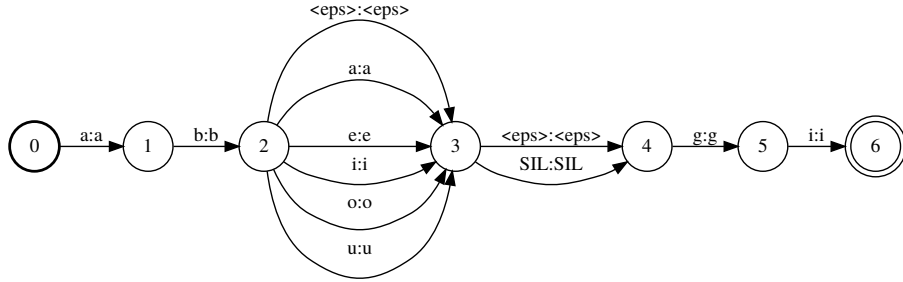


Figure 3.1: Constrained language model used for decoding the stimulus /abgi/. Nodes in the graph represent states, edges represent transitions between states (here: phonemes). The lack of weights on edges issued from a same node (e.g., between states 2 and 3) indicates that path selection is entirely decided by acoustic scores when decoding experimental items. An optional silence can be inserted by the model between states 3 and 4.

Data analysis

Using scores from our model, we simulated the perceptual experiment described in section 2.2.2, as explained in section 3.1.4. In order to assess the role of duration on the choice of epenthetic vowel quality, we inferred the *a posteriori* distributions of the weights given to acoustic model, language model, and duration scores in [equation 2.15](#), using ABC. The following aggregated data were used as summary statistics:

- %none: Proportion of “none” responses (no epenthesis)

- $\%V_1 \vee V_2$: Proportion of vowel copy where the epenthesized vowel shares the quality of either V_1 or V_2 , with $V_1 \neq V_2$)
- $\%V_1 \wedge V_2$: Proportion of vowel copy where the epenthesized vowel shares the quality of both V_1 and V_2 , with $V_1 = V_2$)
- $\%\text{default}$: Proportion of default /u/-epenthesis over all trials
- $\%\text{coronal}$: Proportion of /o/-epenthesis following coronal consonants over all trials with clusters containing coronal consonants

3.2.3 Results

3.2.4 Discussion

3.3 m-/ahpa/

3.3.1 Introduction

3.3.2 Methods

Stimuli

We used the same stimuli as in section 2.1. As a reminder, we recorded 3 speakers producing disyllabic $V_1C_1C_2V_1$ and trisyllabic $V_1C_1V_2C_2V_1$, with V_1 a flanking vowel in the set /a, e, i, o, u/, C_1 /h/ or /k/, and C_2 a fixed consonant, /p/ (e.g., /ahpa/, /ahapa/). By splicing the disyllabic natural control items (e.g., /ahpa/), we obtained disyllabic spliced control items (e.g., /ah_apa/), disyllabic spliced test stimuli (e.g., /ah_upa/), and trisyllabic spliced fillers (e.g., /ahapa/). Therefore, within each speaker, all stimuli of the same structure (in our example, /ah(V)pa/ items) are acoustically identical on their flanking vowels.

Language models

In this section, we investigate the type of phonotactic information used by Japanese listeners when perceiving foreign speech that does not conform to native phonotactics. We test 5 types of language models (LM):

1. A null language model (0P-LM), which implies that listeners base their decoding of consonant clusters on phonetics alone, without using information on phonotactics (similar to that used in section 3.2)
2. A phone-unigram language model (1P-LM), which implies that listeners do not take neighbouring phonemes into consideration when decoding the consonant clusters
3. An online phone-bigram language model (2PO-LM), which implies that listeners decode the clusters as they hear them (decoding is done from the start of the item)

4. A retro phone-bigram language model (2PR-LM), which implies that listeners decode the clusters based on the most recent information (decoding is done from the end of the item)
5. A batch phone-bigram language model (2PB-LM), which implies that listeners decode the item considering the entire structure, with bigrams

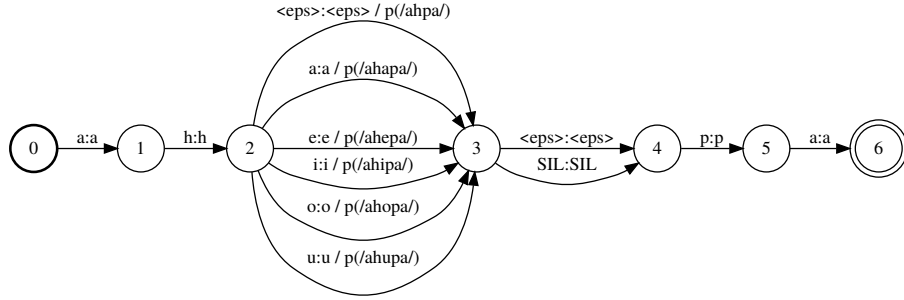


Figure 3.2: Constrained language model used to test the models (here: LM for /ahpa/ trials). Nodes in the graph represent states, weighted edges represent transitions between states (here: phonemes). When relevant, weighted edges are labeled with the probability to choose that edge when decoding, which affects the final language model score of each possible path. These scores are then combined with acoustic and duration scores when decoding experimental items.

Data analysis

3.3.3 Results

3.3.4 Discussion

Chapter 4

Chapter Four Title

Chapter 5

Chapter Five Title

Chapter 6

General Discussion

Are words easier to learn from infant- than adult-directed speech? A quantitative corpus-based investigation

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We investigate whether infant-directed speech (IDS) could facilitate word form learning when compared to adult-directed speech (ADS). To study this, we examine the distribution of word forms at two levels, acoustic and phonological, using a large database of spontaneous speech in Japanese. At the acoustic level we show that, as has been documented before for phonemes, the realizations of words are more variable and less discriminable in IDS than in ADS. At the phonological level, we find an effect in the opposite direction: the IDS lexicon contains more distinctive words (such as onomatopoeias) than the ADS counterpart. Combining the acoustic and phonological metrics together in a global discriminability score reveals that the bigger separation of lexical categories in the phonological space does not compensate for the opposite effect observed at the acoustic level. As a result, IDS word forms are still globally less discriminable than ADS word forms, even though the effect is numerically small. We discuss the implication of these findings for the view that the functional role of IDS is to improve language learnability.

Keywords: speech perception, psycholinguistics, language development, word learning, infant-directed speech, hyperspeech

1 Introduction

Infants' language acquisition proceeds at an amazing speed despite the inherent difficulties in discovering linguistic units such as phonemes and words from continuous speech. A popular view holds that part of the problem may be alleviated by the infants' caregivers, who may simplify the learning task when they speak to their infants in a particular register called infant-directed speech (IDS). In this paper, we compare IDS and adult-directed speech (ADS) in terms of dimensions that are relevant for the learnability of sound categories. We first review alternative hypotheses about a possible facilitatory role of IDS.

1.1 IDS-ADS differences in the context of learnability

The notion that particular speech registers may have articulatory and acoustic properties that enhance speech perception may have been first introduced by Lindblom in the context of his Hyper and Hypo-articulation (H&H) theory (1990). In the case of hyperarticulation, the resulting listener-oriented modifications are referred to as 'hyperspeech'. Here, the priority is to enhance differences

among contrasting elements, and it runs counter the speaker-oriented tendency to produce more economical articulatory sequences.

Fernald (2000) proposed a more general definition of hyperspeech in the context of language acquisition. The idea is that parents may manipulate linguistic levels other than articulatory ones, such as information relating to word frequency or neighborhood density, resulting in facilitated perception:

"[T]he hyperspeech notion should not be confined to articulatory factors at the segmental level, but should be extended to a wider range of factors in speech that facilitate comprehension by the infant".

While the hyperspeech notion initially refers to a modification of language as to enhance perception, Kuhl et al. (1997) go one step further, positing that IDS register-specific modifications may also enhance *learning*:

"Our findings demonstrate that language input to infants has culturally universal characteristics designed to promote language learning".

We call this last hypothesis the *Hyper Learnability* Hypothesis (HLH). It goes beyond the hyperspeech hypothesis in that it refers not to perception but to the language learning processes operating in the infant. Importantly, these two notions may not necessarily be aligned. In some instances, both hyperspeech and HLH are congruent with the usually reported properties of IDS: exaggerated prosody and articulation (Fernald et al., 1989; Soderstrom, 2007), shorter sentences (Phillips, 1973; Newport, Gleitman, & Gleitman, 1977; Fernald et al., 1989), simpler syntax (Phillips, 1973; Newport et al., 1977), and slower speech rate (Fernald et al., 1989; Englund & Behne, 2005) (see Soderstrom, 2007; Golinkoff, Can, Soderstrom, & Hirsh-Pasek, 2015 for more comprehensive reviews). All of these properties are plausible candidates for facilitating both language perception and language learning at the relevant linguistic levels — namely phonetic, prosodic, lexical and syntactic — by making these features more salient or more contrastive to the infant. Yet, in other instances, perception and learning may diverge. As Kuhl (2000) notes:

“Mothers addressing infants also increase the variety of exemplars they use, behaving in a way that makes mothers resemble many different talkers, a feature shown to assist category learning in second-language learners.”

In this case, increase in variability, which is known to negatively affect speech perception in both adults and children (see Mullenix, Pisoni, & Martin, 1989; Ryalls & Pisoni, 1997; Bergmann, Cristia, & Dupoux, 2016) is nevertheless hypothesized to positively affect learning in infants. Work by Rost and McMurray (2009) suggests that this might be the case for 14-month-old infants learning novel word-object mappings. However, it appears that not any kind of variability will do; only increased variability in certain cues — specifically those irrelevant to the contrasts of interest — promoted learning of word-object mappings (Rost & McMurray, 2010). This illustrates the very important point that HLH cannot be empirically tested independently of a specific hypothesis or theory of the learning process in infants. Ideally, the hypothesis or theory should be explicit enough that it could be implemented as an algorithm, which derives numerical predictions on learning outcomes when run on speech corpora of ADS and IDS (Dupoux, 2016). Unfortunately, as of today, such algorithms are not yet available for modelling early language acquisition in infants. Yet, a reasonable alternative is to resort to measurements that act as a *proxy* for learning outcomes within a given theory.

In the following, we focus on a component of language processing which has been particularly well studied: speech categories. For this component, a variety of theories have been proposed, which can be separated in two types: bottom-up theories and top-down theories. We review these two

types in the following sections and discuss possible proxies for them.

1.2 Bottom-up theories: Discriminability as a proxy

Bottom-up theories propose that phonetic categories emerge from the speech signal; they are extracted by attending to certain phonetic dimensions (Jusczyk, Bertoncini, Bijeljac-Babic, Kennedy, & Mehler, 1990), or by identifying category prototypes (Kuhl, 1993). More explicitly, Maye, Werker, and Gerken (2002) proposed that infants construct categories by tracking statistical modes in phonetic space. This idea can be made even more computationally explicit by using unsupervised clustering algorithms, such as Gaussian mixture estimation (De Boer & Kuhl, 2003; Vallabha, McClelland, Pons, Werker, & Amano, 2007; McMurray, Aslin, & Toscano, 2009; Lake, Vallabha, & McClelland, 2009), or self-organizing neural maps (Kohonen, 1988; Guenther & Gjaja, 1996; Vallabha et al., 2007). Given the existence of such computational algorithms, it would seem easy to test if IDS enhances learning by running them on IDS and ADS data, and then evaluating the quality of the resulting clusters.

However, this is not so simple for two reasons. First, each of the above-mentioned algorithms makes different assumptions about the number, granularity, and shape of phonetic categories, parameters which could potentially lead to different outcomes. Even more problematic is that this subset of algorithms does not exhaust the space of possible clustering algorithms. Since we do not know which of these assumptions and algorithms are those that best approximate computational mechanisms used by infants, applying these algorithms to data may not get us any closer to a definitive answer. Second, these particular algorithms have only been validated on artificially simplified data (e.g., representing categories as formant measurements extracted from hand-segmented data) and not on a corpus of realistic speech. In fact, when similar algorithms are run on real speech, they fail to learn phonetic categories; instead they learn smaller and more context-dependent units (e.g., Varadarajan, Khudanpur, & Dupoux, 2008; see also Antetomaso et al., 2016). The unsupervised discovery of phonetic units is currently an unsolved problem which gives rise to a variety of approaches (see Versteegh, Anguera, Jansen, & Dupoux, 2016 for a review).

Given the unavailability of effective phoneme discovery algorithms that could test the bottom-up version of HLH, many researchers have adopted a more indirect approach using descriptive measures of phonetic category distributions as a *proxy* for learnability. Here we review two such proxies: *category separation* and *category discriminability*.

Category separation corresponds to the distance between the center of these categories in phonetic space. Kuhl et al. (1997) measured the center of the ‘point’ vowels /a/, /i/, and /u/ in formant space, in ADS and IDS, across three

languages (American English, Russian and Swedish). Results revealed that the spatial separation between the center of these vowels was increased in IDS compared to ADS. This observation has been replicated in several studies (Bernstein Ratner, 1984; Andruski, Kuhl, & Hayashi, 1999; Burnham, Kitamura, & Vollmer-Conna, 2002; Liu, Kuhl, & Tsao, 2003; Uther, Knoll, & Burnham, 2007; Cristia & Seidl, 2014; McMurray, Kovack-Lesh, Goodwin, & McEchron, 2013, although see Benders, 2013). However, it is less clear that separation generalizes to other segments beyond the three point vowels. For instance, Cristia and Seidl (2014) attested increased separation of the point vowels in speech spoken to 4- and 11-month old learners of American English, but not for other vowel contrasts (e.g., [i-i]). The between-category distance among the latter vowel categories was not larger in IDS than in ADS (see also McMurray et al., 2013 for similar results). This is problematic for learnability because one might argue on computational grounds that the vowels that are difficult to learn are probably not the point vowels which are situated at the extreme of the vocal space, but rather the ones that are in the middle and have several competitors with which they can be confused.

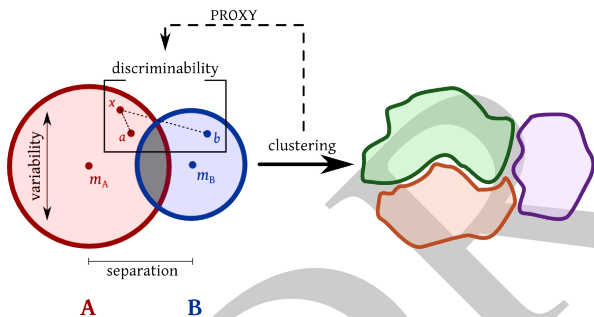


Figure 1. Schematic view of separation, variability and discriminability between two categories A and B (left), and a possible clustering obtained from the distributions (right). *Separation* measures the distance between the center of categories A and B; it is computed as the distance between the medoids m_A and m_B . *Variability* measures the spatial spread of tokens within a given category; it is computed as the average distance between tokens in a category. *Discriminability* depends on both variability and separation; it is quantified with an ABX score as the probability that a given token x (say, of A) is less distant to another token a of A than to a token b of B.

There is another reason to doubt that separation is a very good proxy in the first place. As shown in Figure 1, categories are defined not only by their center, but also by their

variability. If, for instance, IDS not only increases the separation between category centers compared to ADS, but also increases within category variability, the two effects could cancel each other out or even wind up making IDS more difficult to learn. In fact, as we mentioned above, Kuhl et al. (1997) reported that parents tend to be more variable in their vowel productions in IDS than ADS. This was confirmed in later studies (Kirchhoff & Schimmel, 2005; McMurray et al., 2013; Cristia & Seidl, 2014). If so, what is the net effect of these two opposing tendencies on category learnability?

Previous work by Schatz (2016) has shown that the performance of unsupervised clustering algorithms can be predicted by a psychophysically-inspired measure: the ABX *discrimination score*. The intuition behind this measure is illustrated in Fig. 1: it is defined as the probability that tokens within a category are closer to one another than between categories. If the two categories are completely overlapping, the ABX score is 0.5. If, on the other hand, the two categories are well segregated, the score can reach 1¹. This work has demonstrated that the ABX score tends to be more statistically stable than standard clustering algorithms (k-nearest neighbors, spectral clustering, hierarchical clustering, k-means, etc.) while predicting their outcomes better than they predict each other's outcomes. All in all, this method is independent of specific learning algorithms, is non-parametric (i.e. it does not assume particular shapes of distributions) and can operate on any featural representation including raw acoustic features. It can therefore be used as a stable proxy of unsupervised clustering and, therefore, of bottom-up learnability.

Using this measure, Martin et al. (2015) systematically studied the discriminability of 46 phonemic contrasts of Japanese by running the ABX discriminability test on a speech corpus with features derived from an auditory model, namely mel spectral features. The outcome was that, on average, phonemic categories were actually *less discriminable* in IDS than in ADS. While most contrasts did not differ between the two registers, the few that systematically differed pointed rather towards a decrease in acoustic contrastiveness in IDS at the phonemic level.

To sum up, if one uses ABX-discriminability as a proxy for bottom-up learnability, we can conclude that the HLH is not supported by the data available. However, bottom-up learning is not the only theoretical option available to account for phonetic learning in infants. Next, we examine top-down theories.

1.3 Top-down theories: Three learnability subproblems

Top-down theories of phonetic category learning share with linguists the intuition that phonemes are defined, not

¹Schatz (2016) has shown that an ABX score of 1 between categories A and B implies that the two categories can be discovered without error by the clustering algorithm k-means.

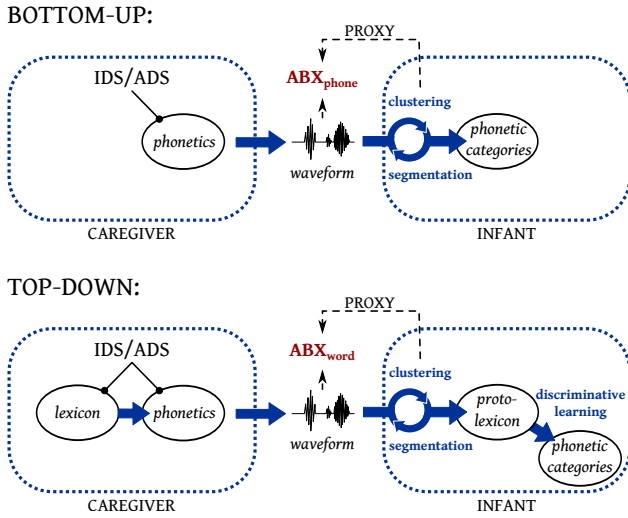


Figure 2. Schematic view of (a) bottom-up and (b) top-down models of phonetic learning, together with ABX discriminability as a proxy for measuring the effect of ADS versus IDS on learnability.

so much through their acoustic properties, but rather through their function. The function of phonemes is to carry meaning contrasts at the lexical level. Top-down theories therefore posit that phonemes emerge from the lexicon. As stated by Werker and Curtin (2005) (see also Beckman & Edwards, 2000):

“As the vocabulary expands and more words with overlapping features are added, higher order regularities emerge from the multidimensional clusters. These higher order regularities gradually coalesce into a system of contrastive phonemes.” (p. 217)

There are many ways to flesh out these ideas in terms of computational mechanisms. All of them involve at least the requirement that (some) word forms are learned and that these forms constrain the acquisition of phonetic categories. This can be summarized in terms of three subproblems (Fig. 2b): (1) segmenting word tokens from continuous speech, (2) clustering said word tokens into types, (3) using said types to learn phonetic categories via a contrastive mechanism. Arguably, these three subproblems are interdependent (in fact, some models address several of them jointly, e.g., Feldman, Griffiths, & Morgan, 2009 or iteratively, e.g., Versteegh et al., 2016), and only a fully specified model would enable to fully test the functional impact of IDS for learnability under such a theory. Yet, as above, we claim that one can develop measures that can act as proxies for learnability, even in the absence of a full model.

In what follows, we focus on the second subproblem, i.e., the clustering of word types, which we take to be of central importance for phonetic category learning. Indeed, in case of a failure to solve subproblem 1 (e.g., infants undersegment “the dog” into “thedog”, or oversegment “butterfly” into “butter fly”), it is still possible to use contrastive learning with badly segmented proto-words to learn phonetic categories (Fourtassi & Dupoux, 2014). In contrast, in case of a failure to solve subproblem 2, (e.g., infants merge “cat” and “dog” into a signal word type, or split “tomato” into many context or speaker dependant variants) then it is much more dubious that contrastive learning can be of any help to establish phonetic categories. Our experiments therefore only address subproblem 2, and we come back to the other two subproblems in the General Discussion.

1.4 The present study: word form discriminability

The construction of word form categories is a similar computational problem to the problem of constructing phonetic categories discussed above. Both can be formulated as unsupervised clustering problems, the only difference being the granularity and number of categories being formed. Instead of sorting out instances of ‘i’, ‘a’ and ‘o’ into clusters, the problem is to sort out instances of ‘cat’, ‘dog’ and ‘tomato’ into clusters. Therefore in both instances, it is possible to use ABX discriminability as a proxy for the (bottom-up) learnability of these categories. Of course, words being composed of phonemes, one would expect a correlation between ABX discriminability on phonemes and on words. However, the word form level introduces two specific types of effects making such a correlation far from trivially true.

First, the word level typically introduces specific patterns of phonetic variability. For instance, the word ‘tomato’ can be produced in a variety of ways: /t^həˈmeɪrou/, /təˈmeɪtə/, /təˈmatəv/, etc. Some of these variations are dependant on the dialect but others can surface freely within speaker, or depending on context, speaking style, or speaking rate. Such phonetic effects translate into distinct acoustic realizations of the word forms, potentially complicating the task of word form category learning. Could it be that IDS limits this source of variation, thereby helping infants to construct word form categories? Some studies have shown the use of more canonical forms in IDS than ADS (e.g., Dilley, Millett, McAuley, & Bergeson, 2014), while others have not (e.g., Fais, Kajikawa, Amano, & Werker, 2010; Lahey & Ernestus, 2014), but to our knowledge no study has looked at the global effect of these variations on word discriminability, and done so systematically. This is what we will examine in Experiment 1.

Second, and setting aside phonetic realization to focus on abstract phonological characteristics, words tend to occupy sparse regions of phonological space. Put differently, there are many more unused possible word forms than actual

ones. This results in minimal pairs being generally rare. For instance, a corpus analysis reveals that, in English, Dutch, French, and German, minimal pairs will concern less than 0.1% of all pairs (Dautriche, Mahowald, Gibson, Christophe, & Piantadosi, 2017); in fact, two words selected at random will differ in more than 90% of their phonemes on average. This should make word form clustering an easier task than phonetic clustering, a welcome result for top-down theories. However, it could be that IDS modulates this effect by containing a different set of words than the vocabulary directed to adults. Corpora descriptions of IDS suggest that this is the case: Caregivers use a reduced vocabulary (Phillips, 1973; Kaye, 1980; Henning, Striano, & Lieven, 2005), which often includes a set of lexical items with special characteristics, such as syllabic reduplications and mimetics (Ferguson, 1964; Fernald & Morikawa, 1993; Mazuka, Kondo, & Hayashi, 2008). May IDS boost learning by containing more phonologically distinct word forms than ADS? This is what we will examine in Experiment 2.

The overall learnability of word forms, as far as clustering is concerned, is the combined effect of phonetic/acoustic discriminability (isolated in Experiment 1) and phonological discriminability (isolated in Experiment 2). As these two factors may go in different directions, we study the global discriminability of IDS versus ADS word form lexicons in Experiment 3.

1.5 Japanese IDS

Like other variants of IDS around the globe (Ferguson, 1964), Japanese IDS is characterized by the presence of Infant-Directed Vocabulary (IDV), ‘babytalk’ specifically used when interacting with infants. According to a survey and corpora studies by Mazuka et al. (2008), these words are mostly phonologically unrelated to words in the ADS lexicon. In particular, IDV presents many instances of reduplications (around 65%) and onomatopoeias/mimetic words (around 40%).² Phonological structures found in IDV are, in fact, more similar to phonological patterns produced by Japanese infants earlier in development than to patterns found in the adult lexicon (Tsuji, Nishikawa, & Mazuka, 2014; a list of 50 earlier produced words is given by Iba, 2000). In addition to pattern repetition within words, IDS also presents more content word repetition, as well as more frequent and longer pauses, making utterances in IDS shorter than in ADS (Martin, Igarashi, Jincho, & Mazuka, 2016).

Regarding the phonetics of Japanese IDS, it presents pitch-range expansion (Igarashi, Nishikawa, Tanaka, & Mazuka, 2013), but it is not slower than ADS when taking into account local speech rate (Martin et al., 2016). More related to our question of phonetic categories, vowel space expansion in F1 x F2 space has been attested in Japanese IDS (Andruski et al., 1999; Miyazawa, Shinya, Martin, Kikuchi, & Mazuka, 2017); however, IDS categories presented higher

Table 1

Description of the base corpora for ADS and IDS

	ADS	IDS
Duration	3 hours	11 hours
Types	1,382	1,765
Tokens	12,248	34,253

variability and overlap (Miyazawa et al., 2017), consistent with the decrease of acoustic discriminability observed by Martin et al. (2015). In fact, contrary to intuition, IDS appears to present more devoicing of non-high vowels than ADS (i.e., less canonical and identifiable tokens), due to breathiness (Martin, Utsugi, & Mazuka, 2014). This paralinguistic modification of speech, which is thought to convey affect, is more prevalent in IDS than ADS (Miyazawa et al., 2017).

1.6 Corpus

Most of the Japanese studies cited above, as well as the work described in this paper, have used data from the RIKEN Japanese Mother-Infant Conversation Corpus, R-JMICC (Mazuka, Igarashi, & Nishikawa, 2006), a corpus of spoken Japanese produced by 22 mothers in two listener-dependent registers: infant-directed speech (IDS) and adult-directed speech (ADS) (Igarashi et al., 2013).

For our study, a word was defined as a set of co-occurring phonemes with word boundaries following the gold standard for words in Japanese, roughly corresponding to dictionary entries. Lexical derivations were considered to belong to a separate type category with respect to their corresponding lemmas. For instance, /nai/ and /aru/, inflections of the verb ある /aru/ (English: *to be*), were evaluated as separate words. Homophones were collapsed into the same word category in the analyses.

Because of the emphasis given to phonological structure when defining word categories, devoiced vowels were considered to be phonologically identical to their voiced counterparts, and similarly for abnormally elongated vowels or consonants that did not result in lexical modifications (i.e. use of gemination for emphasis). Additionally, fragmented, mispronounced, and unintelligible words were not included in our analyses (approximately 5,34% out of the initial corpus). The resulting corpus is henceforth referred to as the *base corpus*; information about its content can be found in Table 1.

²In a study by Fernald and Morikawa (1993), Japanese mothers used onomatopoeic words more readily than American mothers.

2 Experiment 1: Acoustic distribution of word tokens

In this experiment, we ask whether caregivers articulate words in a more or less ‘distinctive’ manner when addressing their infants. Our aim is to answer this question at a purely acoustic level, *i.e.*, taking into account phonetic and acoustic variability, after removing influences from other aspects that vary across registers (e.g., lexical structure). Therefore, the following analyses have been restricted to the lexicon of words that are *common* to IDS and ADS for each parent.

Our main measure is ABX discriminability applied to entire words. As in Martin et al. (2015), we use the ABX_{score} which shows classification at chance with a value of 0.5, while perfect discrimination yields a score of 1. As such, a higher ABX_{score} for IDS than ADS would mean that, on average, parents make their word categories more acoustically discriminable when addressing their infants, making these words easier to learn according to top-down theories.

The ABX discriminability measure implies computing the acoustic distance between word tokens, and computing the probability that two tokens belonging to the same word type are closer to one another than two tokens belonging to two distinct word types.

Since it is the first time that such a discriminability measure is used at the word level, we validate it in a control condition in which there are *a priori* reasons to expect differences in discriminability between two speech registers. Namely, we assess the discrimination of words common to ADS and read speech (RS). This register is typically articulated in a slower, clearer, and more canonical fashion than spontaneous speech. Knowing this, we expect the ABX_{score} to be higher in read speech (RS) than in spontaneous speech (ADS).

Moreover, in order to further validate the application of our method to word units, two additional sub-measures are explored, following the distinctions introduced in Fig. 1: between-category *separation* and within-category *variability*.

2.1 Methods

2.1.1 Control corpus. The Read Speech (RS) subsection of the RIKEN corpus consists of recordings from a subset of 20 out of the 22 parents which had also previously been recorded in the ADS and IDS registers. Participants read 115 sentences containing phonemes in frequencies similar to those of typical adult-directed speech (Sagisaka et al., 1990). We extracted the words that were common to the read and the ADS subcorpora for each individual parent. We obtained between 19 and 32 words, each of them having between 2 and 49 occurrences. All of these word tokens were selected for subsequent analysis in the control ADS vs. RS comparison.

2.1.2 Experimental corpus. All 22 participants had data in the IDS and ADS registers. For each participant, we

selected the words that were common to the two registers. We obtained between 43 and 64 word types (individual numbers can be seen in the Appendix Table A1). All of the word tokens for these types were selected for subsequent analyses in the experimental condition comparing ADS vs. IDS. We did not match IDS and ADS on number of tokens per type to maximize the reliability of the metrics. Since ABX is an unbiased metric of discriminability, the size of a corpus will only modulate the standard error, not the average of the metric. It therefore cannot bias the discriminability score in IDS vs. ADS; simply the fact that the ADS scores are estimated from a smaller corpus means that they will be noisier than the IDS scores. Matching the IDS corpus size to that of ADS would result in increasing the noise in the IDS scores. Number of total tokens per speaker are shown in the Appendix Fig. A1.

2.1.3 Acoustic distance. The three acoustic measures that were computed, namely separation, variability, and discriminability (ABX_{score}), all depend on a common core function which provides the measure of acoustic distance between two word tokens.

As in Martin et al. (2015), we represented word tokens using compressed mel filterbanks, which corresponds to the first stage of an auditory model (Moore, 1997; Schatz, 2016).

Specifically, the audio file of each token was converted into a sequence of auditory spectral frames sampled 100 times per second, obtained by running speech through a bank of 13 band-pass filters centered on frequencies spread according to a mel scale between 100 and 6855 Hz (Schatz et al., 2013). The energy of the output of each of the 13 filters was computed and their dynamic range was compressed by applying a cubic root. In summary, word tokens were represented as sequences of frames, which are vectors with 13-dimensions (*i.e.* 1 value per filter).

The distance between a pair of tokens was computed as follows. First, the two tokens of interest were realigned in the time domain by performing dynamic time warping (DTW; Sakoe & Chiba, 1978): this algorithm searches the optimal alignment path between the sequences of frames of the two tokens that are being compared. The distance between two aligned frames being compared was set to be the angle between the two 13-dimensional feature vectors representing said frames. Secondly, the average of the frame-wise distances along the optimal alignment path was set as the distance between that pair of tokens.

Each of the three measures was computed separately for each speaker, both for IDS and for ADS.

2.1.4 Discriminability. Discriminability calculations were performed as in Martin et al. (2015), by estimating the probability that two tokens within a category are less distant than two tokens in two different categories. This score is computed for each pair of word types, and then aggregated by averaging across all of these pairs (ABX_{score}). The cal-

culations were done using the ABXpy package available on <https://github.com/bootphon/ABXpy>.

More specifically, for each pair of word types A and B , we compiled the list of all possible (a, b, x) triplets where a was a token of category A , b a token of category B and x a token of either A or B . For instance, for word types $A = /nai/$ and $B = /aru/$, there could be a triplet with tokens $a = [nai]_1$, $b = [aru]_1$, and $x = [nai]_2$. The distance $d(a, x)$ between tokens a and x was compared to the distance $d(b, x)$ between tokens b and x . In this example, since both a and x are tokens of category A , we expect the acoustic distance between them to be smaller than their distance to a token belonging to a different category (i.e. token b of type B).

As such, if $d(a, x) > d(b, x)$ (i.e. $[nai]_2$ more similar to $[aru]_1$ than to $[nai]_1$), the response given by the algorithm was deemed to be incorrect and an ABX_{score} of 0 was assigned to that specific triplet. On the other hand, if as expected $d(a, x) < d(b, x)$, the algorithm returned a response deemed as correct and a score of 1 was given to the triplet. A final mean ABX_{score} for all triplets was then computed for each speaker, separately for IDS and ADS, only taking into account word pairs that were observed in both speech registers.

2.1.5 Separation. For each pair of word types, we computed the distance between their medoids. A medoid is defined as the word token which minimizes the average distance to all of the other tokens in that word type. In case of ties, we used a set of medoids, and their scores were averaged. Separation can be viewed as a generalization of the notion of phonetic expansion, except that it applies to entire word forms instead of particular segments (e.g., vowels).

2.1.6 Variability. For each word type, variability was computed as the average distance between each token and every other token within the same word type. By definition, only word types with more than one token were included in the calculation. One can view this measure as analogous to the standard deviation in univariate distributions.

2.2 Results and discussion

Regarding the control condition, we compared the acoustic discriminability of the word types common to ADS and RS. We obtained an average ABX discriminability score per speaker per register (ADS or RS). A paired Student's t -test revealed that words were significantly more discriminable in RS than in ADS ($t(19) = 8.74$; $p < .0001$; *Cohen's d* = 2.68), with RS having an ABX_{score} 0.09 points higher than ADS, on average (ABX_{score} of 92% versus 83%, respectively). As shown in Fig. 3 (panels D and H), all 20 parents showed this effect; individual scores can be found in the Appendix Table A1. In other words, on average the algorithm made twice as many errors classifying word tokens into categories in ADS compared to RS. This confirms that the ABX measure is able

to capture the expected effects of read versus spontaneous speech on acoustic discriminability.

Focusing on the experimental condition, for each of the three measures (discriminability, separation, variability), we computed an aggregate score across word types separately for each parent and register (individual scores can be found in the Appendix Table A1). We then analysed the effect of register by running a paired Student's t -test across parents.

The results are visually represented in Fig. 3. First, the analysis revealed a numerically small but statistically reliable degradation in acoustic discriminability of words in IDS compared to ADS (ABX_{score} IDS: 80% vs. ADS: 84%; $t(21) = -4.73$; $p < .001$; *Cohen's d* = -0.84). This is consistent with the degradation in discriminability previously observed at the level of individual phonemes (McMurray et al., 2013; Martin et al., 2015). Second, the trend for greater separation of word categories in IDS compared to ADS was not statistically significant (IDS: 0.47 rad vs. ADS: 0.46 rad; $t(21) = 1.23$; $p > .05$; *Cohen's d* = 0.21). Finally, there was a reliable increase in variability in IDS relative to ADS (IDS: 0.38 rad vs. ADS: 0.35 rad; $t(21) = 4.28$; $p < .001$; *Cohen's d* = 1.0). This increased variability is consistent with what has been observed at the level of individual phonemes (McMurray et al., 2013; Cristia & Seidl, 2014).

In sum, we found that word discrimination is more easily achieved in ADS than in IDS. This can be analysed as being due to a large increase in variability in IDS which is not being compensated for by a necessary increase in separation. This is in contrast to predictions posited by the *HLH*, but consistent with previous work at the phonemic level (Martin et al., 2015). In a way, this is not a totally surprising result, since by virtue of matching word types across registers, the effect of register on phoneme variability and discriminability is passed on to the level of words. What is new, however, is that the IDS register does not compensate for the phonetic variability by producing more canonical word forms. Next, we examine the content of the lexicon in the two registers.

3 Experiment 2: Phonological density

In this experiment, we focus on the phonological structure of the IDS and ADS lexicons. The core question is whether parents would select a set of words that are somewhat more 'distinctive' in IDS, yielding a sparser lexicon. Such a sparse lexicon could compensate for the increased phonetic variability measured in Experiment 1, thereby helping infants to cluster word forms into types.

We use Normalised Edit Distance (NED) as our main measure of the sparseness of the IDS and ADS lexicons. NED is defined as the proportion of changes (i.e., segmental additions, deletions and substitutions) to be performed in order to transform one word into another. The smaller the edit distance between two words, the more structurally similar they are.

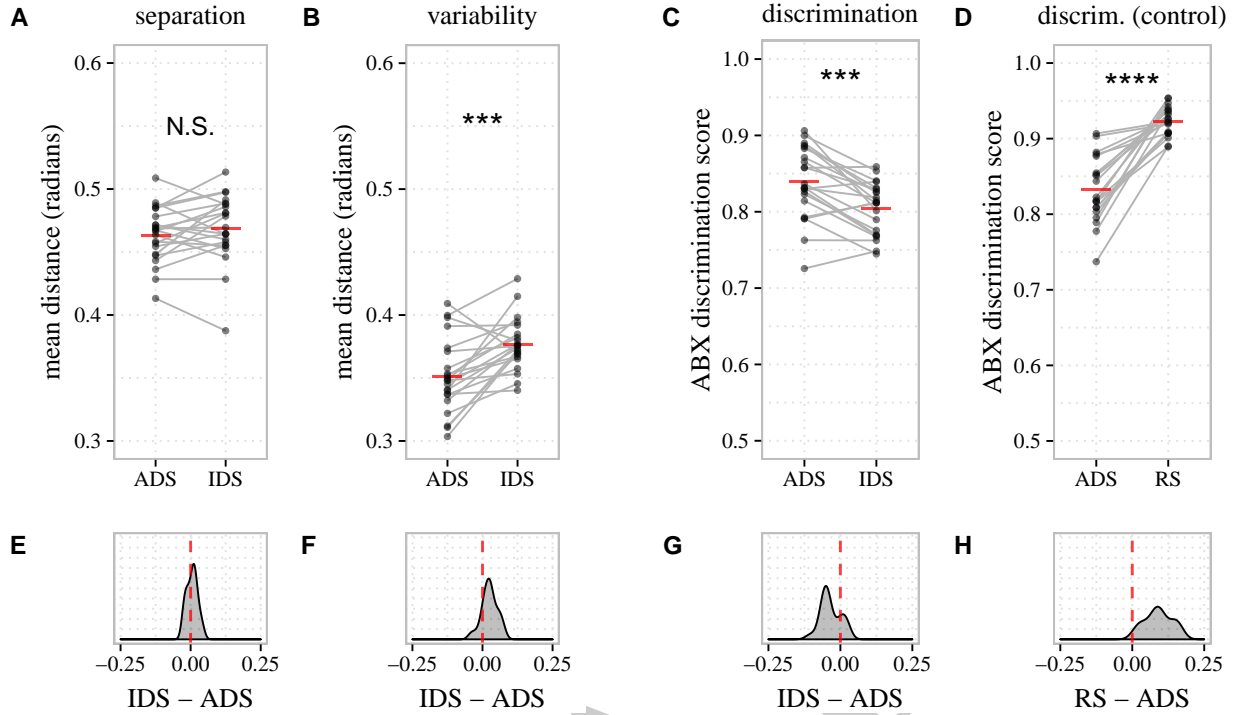


Figure 3. Acoustic distinctiveness scores computed on word types common to IDS and ADS (panels A, B, C, E, F, G), or computed on word types common to ADS and RS (control condition; panels D and H). Upper panels display the distribution of the scores across speakers, as well as means within a speech register (red horizontal lines). Grey lines connect data points corresponding to the same caregiver in both registers (either ADS-IDS or ADS-RS). Bottom panels show the distribution of IDS minus ADS (or RS minus ADS) score differences. Densities to the right of the red zero line denote higher scores for IDS (or RS). A, E: Mean between-category separation (ADS vs. IDS). B, F: Mean within-category variability (ADS vs. IDS). C, G: Mean ABX discrimination score (ADS vs. IDS). D, H: Mean ABX discrimination score (ADS vs. RS; control condition). N.S.: Non-significant difference. ***: $p < .001$. ****: $p < .0001$

NED takes into consideration not only phonological neighbors (i.e. words that differ by one phoneme), but also higher order neighbors when evaluating variation of the phonological structure of the lexicon in a psychologically relevant way. It is the direct phonological equivalent of the *separation* metric used in Experiment 1. Indeed, both metrics measure the average distance between word categories: *separation* measures acoustic distance, while *NED* measures phonological distance. Experiment 1 showed that parents do not reliably expand the acoustic space when using IDS; Experiment 2 asks: Are they expanding the phonological space when using this register?

Before moving on to the analysis, we point out that mean NED may vary with lexicon size. Indeed, as more and more words are added to a lexicon, changes in the neighborhood structure are to be expected. Typically, short words tend to have denser neighborhoods as the lexicon size increases (as the combinatorial possibilities for constructing distinct short words quickly saturate). At the same time, the ratio between

short and long words tends to decrease with lexicon size, because most new additions in a lexicon tend to be long, and long words tend to have sparser neighborhoods than short words. In order to limit the influence of such properties on our results, IDS and ADS corpora were *matched in lexicon size* before any comparison was performed.

3.1 Methods

3.1.1 Sampling. As can be seen in Table 1, the volume of data available for both speaking registers in the *base corpus* was imbalanced; the IDS subset of the corpus contains more words (types and tokens) than its ADS counterpart. In order to account for this mismatch, we performed a frequency-dependent sampling of word types that matched their number in both speech registers. Types which were more frequently uttered by a speaker had a higher probability of being included in a sample than rarer ones. Moreover, since the measurement used in this section heavily relies on the nature of the words sampled, and as a way to increase

estimation reliability, sampling was performed one hundred times per speaker per register. For instance, if a speaker uttered 82 word types in ADS and 237 in IDS, we created 100 subsets of the IDS lexicon by sampling 82 types from the 237 available 100 times. The final metric for said speaker in a given speech register was the mean NED obtained from the corresponding 100 samples. On average, a sample contained 179.64 ± 49 word types (see Table A2 of the Appendix for more information).

3.1.2 Normalized Edit Distance. For each parent, within each speech register, we computed the edit distance (ED) between every possible pair of types in the sampled lexicons. ED, also called the Levenstein distance, is defined as the minimal number of additions, deletions or substitutions needed to transform one string into another. It is computed using an algorithm very similar to the Dynamic Time Warping (DTW) algorithm used in Experiment 1; the algorithm finds a path that minimizes the total number of edits (insertions, deletions and substitutions, all of them equally weighted). The maximal number of changes $\max(x, y)$ is defined as the maximum length of the two types X and Y under comparison. Normalized edit distances (NEDs) were therefore derived as follows:

$$NED_{XY} = \frac{ED_{XY}}{\max(x, y)}$$

where x and y correspond to the phonemic lengths of two distinct words X and Y . For instance, the ED between ‘tall’ /tɔl/ and ‘ball’ /bɔl/ is 1 (one substitution: /t/ \Rightarrow /b/). Both words are 3 phonemes long, so $\max(x, y) = 3$. Therefore, the NED between these types is $\frac{1}{3}$. The more structurally similar two types are, the closer their NED will be to zero.

3.2 Results and Discussion

The distribution of the difference in mean NEDs for IDS and ADS across parents is shown on panels A and C of Fig. 4. Individual scores can be found in the Appendix Table A2. A pair-wise Student’s t -test showed a systematic pattern of larger normalized edit distances in IDS than ADS (IDS: 0.877 vs. ADS: 0.871; $t(21) = 5.00$; $p < .0001$; *Cohen’s d* = 1.38). This difference shows that, overall, the IDS lexicon contains words that are phonologically more distinctive than those in the ADS lexicon. In hindsight, a difference of this sort may have been expected as IDS has been found to contain “babytalk” or infant-directed vocabulary, *i.e.*, a special vocabulary which includes onomatopoeias and phonological reduplications (Ferguson, 1964; Fernald & Morikawa, 1993). This hypothesis was verified in our dataset; we found that onomatopoeias and mimetic words (hereafter referred to solely as “onomatopoeias”) constituted approximately 30% of the average sample of IDS word types used in this experiment, whereas they represented less than 2% of an average

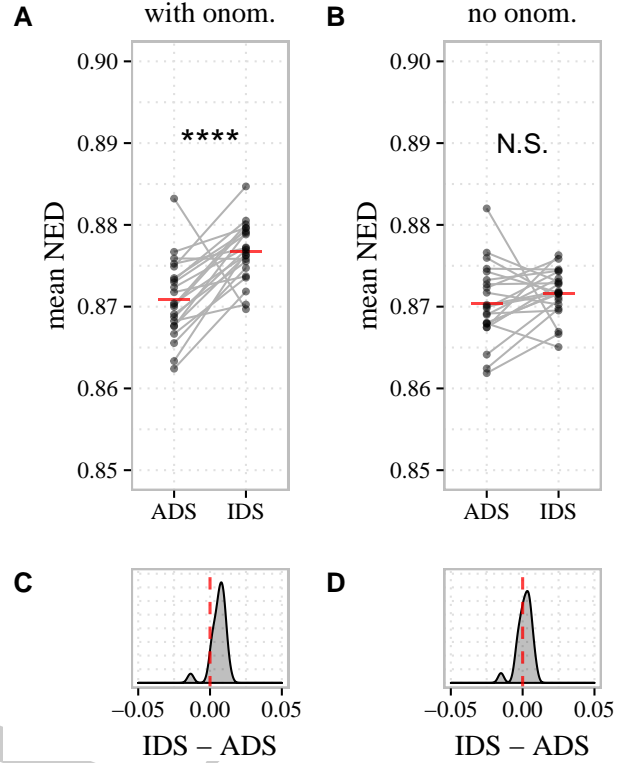


Figure 4. Global phonological density scores (mean NED) for ADS and IDS, computed on lexicons matched for number of types across the two registers. Upper panels display the distribution of the scores across individual speakers, as well as means within a speech register (red horizontal lines). Grey lines connect data points corresponding to the same caregiver in both registers. Bottom panels show the distribution of IDS minus ADS score differences. Densities to the right of the red zero line denote higher scores for IDS. A, C: Samples from base corpus. B, D: Samples from base corpus after onomatopoeia removal. *N.S.*: Non-significant difference. ****: $p < .0001$

ADS sample (*cf.* Appendix Table A2), this latter frequency being consistent with the use of mimetic words in Japanese observed in previous work (Saji & Imai, 2013).

In order to study the effect of onomatopoeias on phonological discriminability, we performed a post-hoc analysis by re-sampling words after removing all onomatopoeias from the base corpus. We then re-computed the mean NED for ADS and IDS. Individual scores can be found in the right side of the Appendix Table A2. A paired Student’s t -test revealed that the previously noted difference between IDS and ADS mean NED scores was no longer significant after onomatopoeia removal (IDS: 0.872 vs. ADS: 0.870; $t(21) = 1.14$; $p > 0.05$; *Cohen’s d* = 0.31, visual representation on panels B and D of Fig. 4). Therefore, the IDS lexicon

con was found to be globally sparser than the ADS lexicon, and this effect seems to be principally driven by the unequal presence of onomatopoeic sounds in both speech registers.

Infant-directed words may facilitate lexical development not only by decreasing the overall phonological density of the lexicon, which directly impacts the clustering subproblem detailed in the introduction, but also in virtue of other intrinsic learning properties that would be relevant in a more complete model of early word learning. In the introduction we focused on the three key word learning subproblems of segmentation, word clustering, and phonetic categorization. At this point, it is imperative to point out that there are other factors that impact word learning in infancy above and beyond these particular processes.

When asked about vocabulary specifically used when addressing infants, Japanese women report a set of words of which 40% of the items are sound-symbolic (Mazuka et al., 2008). An iconic relationship between an acoustic form and the semantics of the referent (Imai & Kita, 2014) has been shown to help 14-months old infants finding a word’s referent (Miyazaki et al., 2013), and it also facilitates the identification by pre-school children of the specific features of an action a verbal word form is referring to (Imai, Kita, Nagumo, & Okada, 2008; Kantartzis, Imai, & Kita, 2011). Additionally, around 65% of the reported items contain reduplication of phonological patterns (Mazuka et al., 2008), which may impact learning at a range of levels. Repetitive patterns may be more salient and generalizable than other equally complex patterns (Endress, Dehaene-Lambertz, & Mehler, 2007; Endress, Nespor, & Mehler, 2009), and this salience could facilitate lexical acquisition in infants. This is supported by recent data showing that 9-month old English-learning infants segment words containing reduplications (e.g. *neenee*) from running speech more easily than words without reduplications (e.g. *neefoo*) (Ota & Skarabela, 2017). Furthermore, English-learning 18-month-old infants appear to better learn novel object labels when these contain reduplications (Ota & Skarabela, 2016). In fact, reduplication has been found to be a characteristic shared by many items from the specialized set of “babytalk” words in various languages (Ferguson, 1964), in spite of the tendency to avoid such repetitive patterns in adult language (Leben, 1973).

Similarly to what was observed in the survey by Mazuka et al. (2008), the majority of the word types tagged as onomatopoeias in our IDS corpus (i.e. around 30% of the types) present reduplication and/or sound symbolism (e.g., *わんわん* /*wanwan*/ *dog*; *ころころ* /*korokoro*/ *light object rolling repeatedly*). Since infants seem to have a learning bias for words with these phonological characteristics, the higher proportion of onomatopoeias in IDS compared to ADS may provide an additional anchor for infant word learning.

As a reviewer pointed out, it may seem counterintuitive

at first to focus on the enhanced learnability of IDS-specific words, since children are expected to eventually master all words, whether they are specific to IDS or present in both IDS and ADS. However, we are not concerned here with all of language acquisition, but only with the possibility that top-down cues affecting sound category learning are more helpful in IDS compared to ADS. Thus, even if the words that are learned are not part of a general target lexicon, they might nonetheless present an easier word clustering subproblem, and in that way lead to a lexicon that can be used as seed for subsequent sound category extraction routines.

In sum, we have found that IDS contains a higher proportion of onomatopoeias and mimetic words than ADS. Aside from their remarkable distinctiveness and salience, these items seem to contribute to decreasing the global density of the IDS lexicon. While words in IDS seem to be more spread in phonological space than words in ADS, phoneme-like representations may not yet be available to infants until a larger vocabulary is amassed (Lindblom, 1992; Metsala & Walley, 1998; Pierrehumbert, 2003; Beckman, Munson, & Edwards, 2007). As such, one may wonder if, similarly, words may be more distant in the acoustic space when taking the structural differences into account. Indeed, we notice that the effect size is almost twice as large for the phonological NED (*Cohen’s d* = −1.38) than for the acoustic discriminability (*Cohen’s d* = −0.84). However, given that they are not based on exactly the same tokens, it remains possible that the phonological advantage does not compensate for the acoustic disadvantage. Indeed, the difference in mean NED between IDS and ADS, while statistically significant, is numerically very small, representing a difference of less than one percent of a word. The following experiment examines the question of the effect of phonological structure on acoustic discriminability, by integrating both factors in one global discriminability measure.

4 Experiment 3: Net Discriminability

In Experiment 1, we found that when we looked at the exact same word types in both registers, the IDS tokens were acoustically more confusable than the ADS tokens, due to the increased variability of IDS word categories in the acoustic space. In other words, when removing the influence of structural peculiarities of the lexicons, IDS does not present an advantage over ADS in acoustic discriminability. We then saw in Experiment 2 that the lexicons of IDS and ADS differed structurally. Words from the IDS lexicon were phonologically more distinct than those in the ADS lexicon, in part due to onomatopoeias and mimetic words.

Here, we put these two previous results together and ask the following question: When accounting for register-specific lexical structure, is the IDS lexicon acoustically clearer than the ADS lexicon? In other words, if we take a random pair of word tokens from two different word types

found in the IDS recordings, are these tokens more or less acoustically distinct than a like-built pair in the ADS recordings?

4.1 Method

4.1.1 Sampling. In order to observe the combined effects of the differences in phonological structure on acoustic discriminability, the same sampled lexicons used for Experiment 2 were used for this section, i.e. 100 lexicon subsets per register per speaker, matched in number of word types across speech registers.

As it was done in Experiment 1, number of tokens per type were not matched in order to maximize the reliability of the ABX metric. Individual number of types can be seen in Table A2 of the Appendix, with total number of tokens shown in the Appendix Fig. A1.

4.1.2 Computing acoustic discriminability. Acoustic discriminability was computed as described in Experiment 1. A mean ABX score was computed per sampled lexicon subset. ABX scores were collapsed by computing the mean ABX score per speaker per register.

4.2 Results and Discussion

We compared the mean ABX scores for ADS and IDS obtained on the sampled lexicons used in Experiment 2 (Fig. 5). Individual scores can be found in the Appendix Table A2. A paired Student's t -test revealed that mean ABX_{score} were significantly larger for IDS than for ADS, whether onomatopoeias were included in the lexicon subsets (ABX_{score} IDS: 86% vs. ADS: 87%; $t(21) = -2.37, p < 0.05$; *Cohen's d* = -0.41) or not (ABX_{score} IDS: 85% vs. ADS: 87%; $t(21) = -2.57, p < 0.05$; *Cohen's d* = -0.43). As such, similar to what was found in Experiment 1, words are less discriminable in IDS than in ADS, even after taking into account the phonological specificities of the infant-directed lexicon.

This result underlines the importance of assessing effects of language acquisition enhancers not only in terms of their statistical significance across parents (p values, *Cohen's d*), but also quantitatively, i.e., in terms of their numerical strength when combined together. To see this more clearly, we computed the increase or decrease in the score under study as a percentage relative to the ADS score taken as a baseline.

In Experiment 1, the decrement in discriminability in IDS was 4% relative to ADS, and this effect was robust across participants (*Cohen's d* = -0.84). In Experiment 2, the increase in NED represented a numerically smaller effect of less than 1% for IDS relative to ADS. This effect was actually even more robust across participants (*Cohen's d* = 1.38). Interestingly, when the two effects are combined (Experiment 3), the outcome is not determined by which effect was more statistically robust across the participants, but by which one was numerically larger. Indeed, the outcome yields a numerically

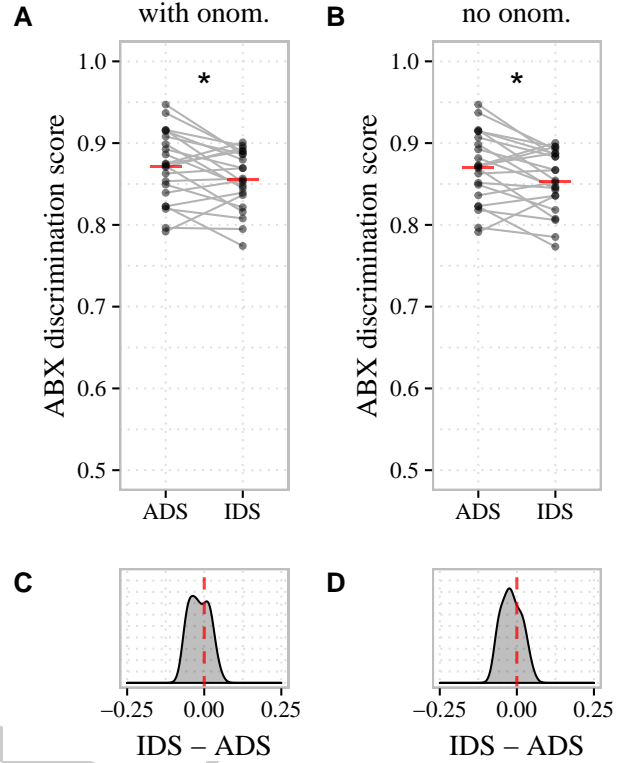


Figure 5. Acoustic-based ABX word discrimination error in ADS and IDS computed on lexicons matched for number of word types across the two registers. Upper panels display the distribution of the scores across speakers, as well as means within a speech register (red horizontal lines). Grey lines connect data points corresponding to the same caregiver in both registers. Bottom panels show the distribution of IDS minus ADS score differences. Densities to the right of the red zero line denote higher error rates for IDS. A, C: Samples from base corpus. B, D: Samples from base corpus after onomatopoeia removal. *: $p < .05$

small (1% relative) decrement in discriminability, which is also much weaker across participants (*Cohen's d* = -0.41).

5 General Discussion

The Hyper Learnability Hypothesis (HLH) states that when talking to their infants, parents modify the linguistic properties of their speech in order to facilitate the learning process. In this paper, we focused on the learning of phonetic categories and reviewed two classes of theories in order to quantitatively assess the HLH: (1) bottom-up theories assume that phonetic categories emerge through the unsupervised clustering of acoustic information, (2) top-down theories assume that phonetic categories emerge through contrastive feedback from learned word types. Previous work

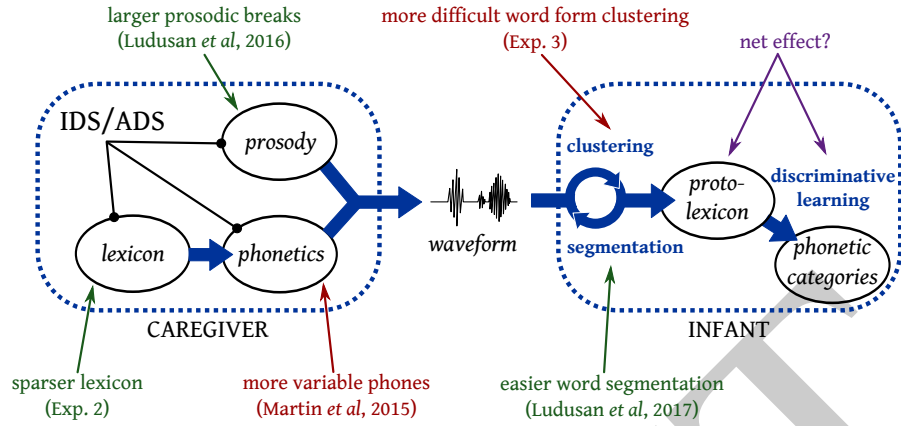


Figure 6. Summary of IDS characteristics relative to ADS in a top-down model of phonetic category learning for the RIKEN corpus. Enhanced characteristics of IDS relative to ADS are shown in green, while those for which the opposite trend is observed are shown in red.

has already addressed bottom-up theories: Martin et al. (2015) examined phonemes in a corpus of Japanese laboratory recordings and found that phonemes produced by caregivers addressing their 18- to 24-month old infants were less discriminable than ADS phonemes. This rules out the HLH for that corpus and bottom-up theories. In the present study, we focused on top-down theories using the same corpus, and investigated the acoustic discriminability of word types.

In Experiment 1, we compared the acoustic discriminability of words that are common to both speech registers, and found that words are *less* discriminable in IDS than in ADS (an absolute decrease in ABX_{score} of 4%), likely because of increased within-category variability. This result parallels the increase in phonetic variability found in previous studies (Kirchhoff & Schimmel, 2005; Cristia & Seidl, 2014; McMurray et al., 2013), and it is consistent with the decreased phoneme discriminability measured by Martin et al. (2015). It is not consistent, however, with the claim that words in IDS are uttered in a more canonical way than in ADS (Dilley et al., 2014, but see Fais et al., 2010; Lahey & Ernestus, 2014). In Experiment 2, we turned to the structure of the phonological lexicon. We found that the IDS lexicon was globally more spread out than that of ADS, as shown by a larger normalized edit distance between words for the former. Interestingly, this effect was attributable mostly to a higher prevalence of onomatopoeias and mimetic words in IDS. These words have idiosyncratic phonological properties, such as reduplications, which are likely responsible for the increase of global distinctiveness found in the IDS lexicon, compared to the ADS lexicon. In Experiment 3, a final analysis measured the net effect of the opposite trends found in Experiments 1 and 2, and found that, on average, words were still less acoustically

discriminable in IDS than in ADS, although the effect was now considerably reduced (an absolute decrease in ABX_{score} of 1%).

Overall, then, the word form clustering subproblem is not easier to solve by using IDS input than with ADS input; quite to the contrary, there is a numerically small but consistent trend in the opposite direction. Does this undermine the HLH for top-down theories of phonetic learning as a whole? Clearly, the answer is “no”, since - as explained in the Introduction - HLH actually encompasses two other learning subproblems. We discuss relevant evidence on IDS-ADS differences bearing on each subproblem in turn.

Regarding the problem of finding word token boundaries, Ludusan and colleagues have started studying word form segmentation using either raw acoustics or text-like phonological representations as input. Ludusan, Seidl, Dupoux, and Cristia (2015) studied the performance of acoustic word form discovery systems on a corpus of American English addressed to 4- or 11-month-olds versus adults. The overall results are similar to those of Experiment 3, i.e., the two registers give similar outcomes, if anything, with a very small difference in favor of ADS, rather than the expected IDS. Computational models of word segmentation from running speech represented via acoustics are, however, well-known to underperform compared to models that represent speech via textual representations (Versteegh et al., 2016). Thus, in Ludusan, Mazuka, Bernard, Cristia, & Dupoux, 2017, we studied word form segmentation from text-like representations using the same RIKEN corpus as input, and a selection of state-of-the-art cognitively-based models of infant word segmentation. Results showed an advantage of IDS over ADS for most algorithms and settings.

Beyond the question of whether segmentation is easier in IDS versus ADS, we cannot move on to the next learning subproblem without pointing out that, for future work to assess the net effect of register on word segmentation, one would need to know more about the size and composition of infants' early lexicon. In fact, most accounts propose that the phonological system is extracted from the long-term lexicon, rather than on the fly from experience with the running spoken input (discussed in Bergmann, Tsuji, & Cristia, 2017). In the present paper, we have done a systematic study of word discriminability across the whole set of words present in the corpus, as if infants could segment the corpus exactly as adults do. This is, of course, unlikely. In fact, recent evidence suggests that infants may be using a sub-optimal segmentation algorithm (Larsen, Dupoux, & Cristia, 2017), which leads them to accumulate a "protolexicon" containing not only words, but also over- or under-segmented tokens that do not belong to the adult-like lexicon (Ngon et al., 2013). Such protowords can nonetheless help with contrastive learning (Martin, Peperkamp, & Dupoux, 2013; Fourtassi & Dupoux, 2014).

Regarding contrastive learning of phonetic categories, it is too early to know whether the net effect of register will be beneficial or detrimental. For instance, a detrimental effect of phonetic variability in a bottom-up setting can become beneficial in a top-down setting, by presenting infants with more varied input, and therefore preparing them for future between-speaker variability. This is illustrated in the supervised learning of phonetic categories in adults (Lively, Logan, & Pisoni, 1993). However, as suggested by Rost and McMurray (2010), variability should be limited to acoustic cues that are not relevant to phonetic contrasts in order to promote learning. In order to fully assess the net effect of register, two important elements have to be clarified. First, one would need to have a fully specified model of contrastive learning itself. Candidate computational models have been proposed (e.g., Feldman et al., 2009; Fourtassi & Dupoux, 2014), but not fully validated with realistic infant-directed speech corpora (but see Versteegh et al., 2016 for an application to ADS corpora).

Throughout the above discussion, an important take-home message is that it is essential to posit well-defined, testable theories of infant learning, which can be evaluated using quantitative measures, even when fully specified computational models are not yet available. Individual studies focus only on few pieces of the puzzle and the magnitude of each evaluated effect must be observed relative to other effects. For instance, in our study, even the relatively large effect of IDS versus ADS on the discriminability of word forms found in Experiment 1 has to be compared to the much larger effect (by a factor of 2) of read versus spontaneous speech found within the ADS register. What we propose as a methodology is to break down theories of language acquisition into com-

ponent parts, and to derive proxy measures for each component to derive a more systematic grasp of the quantitative effects of register. Before closing, we would like to discuss two limitations of the current study, one regarding the corpus and the other regarding the theory tested (the HLH).

The main limitation of the RIKEN corpus is that it was recorded in the laboratory and did not include naturalistic interactions between adults as they may occur in the home environment. The presence of an experimenter and props (toys, etc) in the laboratory setting may induce some degree of non-naturalness in the interaction, both with the infant, and with the adult. Johnson, Lahey, Ernestus, and Cutler (2013) found that in Dutch, ADS is not a homogeneous register, and that it bears similarities with IDS when the addressed adult is familiar as opposed to unfamiliar.³ It remains to be assessed whether similar results are obtained in more ecological and representative IDS and ADS samples. In addition, the current study is limited by the relatively small size of the corpus. Because we analyzed each parent separately, the size of the analyzed lexicons was between 82 and 260 words, which may underrepresent the range of words heard in a home setting. Finally, our analysis is limited to Japanese. There is evidence that vowel hyperarticulation varies across languages (Benders, 2013; Englund & Behne, 2005; Kuhl et al., 1997), and more generally that the specifics of the IDS register varies across culture (e.g., Fernald & Morikawa, 1993; Igarashi et al., 2013). It would therefore be important to replicate our methods in more ecological, cross-linguistic corpora. Fortunately, the availability of wearable recording systems such as the LENA© device (Greenwood, Thiemann-Bourque, Walker, Buzhardt, & Gilkerson, 2011) increases the prospects of automatizing the collection and analysis of naturalistic speech (Soderstrom & Wittebolle, 2013).

The second limitation of the current study is that we restricted our quantitative analysis to the testing of the HLH. However, the HLH is not the only hypothesis that can be addressed. Other theories have been proposed regarding the etiology and role of IDS in the linguistic development of infants (i.e., why caregivers use it, and what are the actual effects on the child). Some modifications of the input may indeed have pedagogical functions (enhancing learnability), while other modifications may decrease learnability while increasing some other factor in the parent-infant interaction. For instance, it has been documented that mothers sometimes violate the grammar of their language when teaching new words, probably in order to place the novel word in a sentence-final position (Aslin, Woodward, LaMendola, & Bever, 1996), which is salient because of properties of short-term memory. Similarly, it has sometimes been suggested that caregivers

³In addition to these effects, Japanese and many other languages have a set of specialized morphemes that depend on familiarity between the talkers; this could have artificially increased the difference between IDS and ADS in the present corpus.

inadvertently sacrifice phonetic precision in order to make infants more comfortable and/or more receptive to the input (Papoušek & Hwang, 1991; Reilly & Bellugi, 1996). Increased phonetic variability in IDS at the phonemic level may stem from a slower speaking rate (McMurray et al., 2013), or from exaggerated prosodic variations (Fernald et al., 1989; Soderstrom, 2007; Martin et al., 2016), or possibly from gestural modifications that convey positive affect, such as smiling (Benders, 2013), increased breathiness (Miyazawa et al., 2017) or even a vocal tract that is shortened to resemble the child's own (Kalashnikova, Carignan, & Burnham, 2017). According to a study by Trueswell et al. (2016), successful word learning interactions tend to be those in which actions performed by both caregivers and infants are precisely synchronised, with time-locking of gaze, speech and gestures. By focusing on efficiently capturing the infant's attention, caregivers could create an optimal learning environment, in spite of potential degradations brought upon lexical acoustic clarity. A similar interpretation is held by authors such as Csibra and Gergely (2006), who argue that one of the main roles of IDS is to inform the infant that speech is being directed to her, thus highlighting the pedagogical nature of the interaction as a whole. In this view, the goal of caregivers would not be to provide clearer input, but to make language interactions and their attached learning situations more exciting and attractive to infants.

Another direction entirely, is to propose that IDS may help infants to *produce* language. Ferguson (1964) describes "babytalk" as a subset of phonologically-simplified words due to reduced consonant clusters, use of coronals instead of velars, word shortening, etc. These adaptations would make it easier for developing infants to imitate the words, and/or they may be inspired by previous generations' production errors. In fact, previous work performed on our corpus shows that, if anything, the structural properties of words in our IDS sample better fit early patterns of Japanese infant speech production than those of words in ADS (Tsuiji et al., 2014). While the causal relationship between babytalk use and infant word production should be further assessed experimentally, the phonological properties of our IDS corpus suggest that, to some extent, parental input may be encouraging infant word production.

In brief, while the HLH focuses on the change in informational content of IDS which may boost (or hinder) the learnability of particular linguistic structures, IDS could have a beneficial effect on completely different grounds: enhancing overall attention or positive emotions which would increase depth of processing and retention, or facilitating production, thereby counteracting the inadvertent acoustic degradation of local units of speech such as words and phonemes. For these alternative theories of HLH to be testable within our quantitative approach, we would need to formulate these theories with enough precision that they can either be implemented,

or proxies can be derived to analyze realistic corpora of caregivers/infants interactions.

To conclude, the last 50 years we have learned a great deal about how IDS and ADS differ, yet much remains to be understood. We believe it is crucial in this quest to bear in mind a detailed model of early language acquisition, and to submit predictions of this model to systematic, quantitative tests.

6 Author contributions

R. Mazuka oversaw the collection and coding of the corpus. A. Martin wrote the algorithms for extracting words and their phonological structure. R. Thiollière provided coding support with the ABX task. A. Cristia directed the literature review. B. Ludusan assisted with preparation of the ADS-RS comparison. A. Guevara-Rukoz and E. Dupoux carried out the acoustical and phonological analyses and, along with A. Cristia, produced the first draft. All authors contributed to the writing of this manuscript.

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Appendices

Table A1

Acoustic discriminability comparisons on common words in ADS vs. IDS, and in ADS vs. RS (Experiment 1). Individual scores for separation (in radians), variability (in radians) and overall acoustic discrimination.

Speaker	#Types	ADS vs. IDS						ADS vs. RS (control)		
		Separation		Variability		ABX _{score}		#Types	ABX _{score}	
		ADS	IDS	ADS	IDS	ADS	IDS		ADS	RS
F039	43	0.47	0.45	0.35	0.38	0.83	0.77	19	0.82	0.94
F047	67	0.47	0.49	0.34	0.37	0.87	0.83	25	0.88	0.92
F118	66	0.49	0.50	0.39	0.39	0.79	0.81	23	0.79	0.95
F233	64	0.41	0.39	0.34	0.36	0.79	0.74	25	0.78	0.93
F302	54	0.49	0.50	0.40	0.43	0.76	0.75	24	0.79	0.89
F367	70	0.46	0.45	0.32	0.35	0.88	0.84	26	0.81	0.94
F478	71	0.44	0.48	0.35	0.40	0.87	0.78	28	0.80	0.93
F483	69	0.46	0.48	0.35	0.37	0.83	0.84	23	0.80	0.91
F484	81	0.45	0.46	0.37	0.39	0.85	0.77	32	0.82	0.95
M002	73	0.46	0.46	0.31	0.37	0.91	0.85	27	0.90	0.92
M013	67	0.45	0.46	0.30	0.37	0.89	0.83	31	0.88	0.93
M024	77	0.48	0.49	0.35	0.38	0.89	0.85	31	0.85	0.93
M025	43	0.49	0.46	0.31	0.37	0.89	0.83	21	0.88	0.91
M044	86	0.47	0.46	0.35	0.38	0.86	0.83	32	0.85	0.93
M120	46	0.45	0.49	0.34	0.41	0.80	0.79	19	0.82	0.89
M125	59	0.48	0.51	0.33	0.38	0.90	0.85	31	0.91	0.92
M312	94	0.47	0.48	0.37	0.38	0.83	0.77	29	0.81	0.91
M374	90	0.47	0.46	0.35	0.37	0.87	0.81	-	-	-
M417	57	0.43	0.45	0.40	0.38	0.73	0.75	-	-	-
M425	78	0.44	0.45	0.34	0.34	0.86	0.86	27	0.82	0.9
M432	49	0.41	0.41	0.41	0.37	0.79	0.81	23	0.81	0.91
M480	68	0.45	0.47	0.36	0.38	0.83	0.82	32	0.84	0.94
Mean		0.46	0.47	0.35	0.38	0.84	0.80	26.4	0.83	0.92
SD	14.41	0.02	0.02	0.03	0.02	0.05	0.03	4.3	0.04	0.02

Table A2

Phonological and acoustic discriminability comparisons in ADS vs. IDS (Experiments 2 and 3). Individual mean NED and overall acoustic discrimination before and after removal of onomatopoeias. Values are computed as the mean of the corresponding values from 100 word samplings per speaker.

Speaker	#Types	With onomatopoeias						#Types	No onomatopoeias			
		%onom.		NED		ABX _{score}			NED		ABX _{score}	
		ADS	IDS	ADS	IDS	ADS	IDS		ADS	IDS	ADS	IDS
F039	82	6.1	35.4	0.883	0.870	0.85	0.82	77	0.882	0.867	0.85	0.82
F047	178	2.2	20.2	0.873	0.879	0.90	0.84	174	0.873	0.873	0.9	0.84
F118	139	1.4	26.6	0.876	0.876	0.84	0.85	137	0.876	0.871	0.84	0.85
F233	167	1.8	22.2	0.869	0.876	0.82	0.77	164	0.869	0.872	0.82	0.77
F302	117	0.9	50.4	0.877	0.880	0.80	0.79	116	0.877	0.873	0.8	0.79
F367	187	1.1	39.0	0.873	0.879	0.91	0.88	183	0.872	0.876	0.91	0.89
F478	221	3.2	8.1	0.870	0.876	0.82	0.81	217	0.869	0.873	0.82	0.81
F483	168	0	37.5	0.870	0.880	0.87	0.89	168	0.870	0.873	0.87	0.90
F484	250	0.8	18.0	0.872	0.874	0.85	0.85	232	0.872	0.870	0.85	0.85
M002	194	2.1	27.3	0.868	0.876	0.92	0.87	190	0.867	0.872	0.92	0.85
M013	196	2.0	19.9	0.867	0.874	0.91	0.87	175	0.868	0.872	0.91	0.88
M024	229	1.3	31.0	0.863	0.877	0.92	0.90	226	0.862	0.870	0.91	0.90
M025	120	0.8	30.0	0.873	0.881	0.94	0.89	119	0.873	0.874	0.94	0.89
M044	212	1.9	29.7	0.875	0.877	0.87	0.89	208	0.874	0.872	0.87	0.89
M120	102	1.0	63.7	0.868	0.879	0.87	0.82	101	0.867	0.876	0.87	0.81
M125	194	1.0	24.2	0.862	0.872	0.95	0.87	192	0.862	0.867	0.95	0.88
M312	248	2.8	24.6	0.868	0.870	0.86	0.87	241	0.868	0.865	0.86	0.87
M374	260	1.9	19.6	0.866	0.875	0.87	0.87	255	0.864	0.871	0.89	0.87
M417	156	0.6	34.6	0.870	0.880	0.79	0.84	155	0.870	0.872	0.79	0.84
M425	191	3.7	20.4	0.877	0.877	0.87	0.90	184	0.870	0.874	0.87	0.90
M432	139	0.7	3.9	0.866	0.877	0.87	0.84	138	0.869	0.870	0.82	0.84
M480	202	2.0	27.7	0.875	0.885	0.89	0.85	185	0.875	0.875	0.88	0.85
Mean	179.64	1.79	29.6	0.871	0.874	0.87	0.86	174.14	0.870	0.872	0.87	0.85
SD	48.72	1.21	12.18	0.005	0.004	0.04	0.04	46.11	0.005	0.003	0.04	0.04

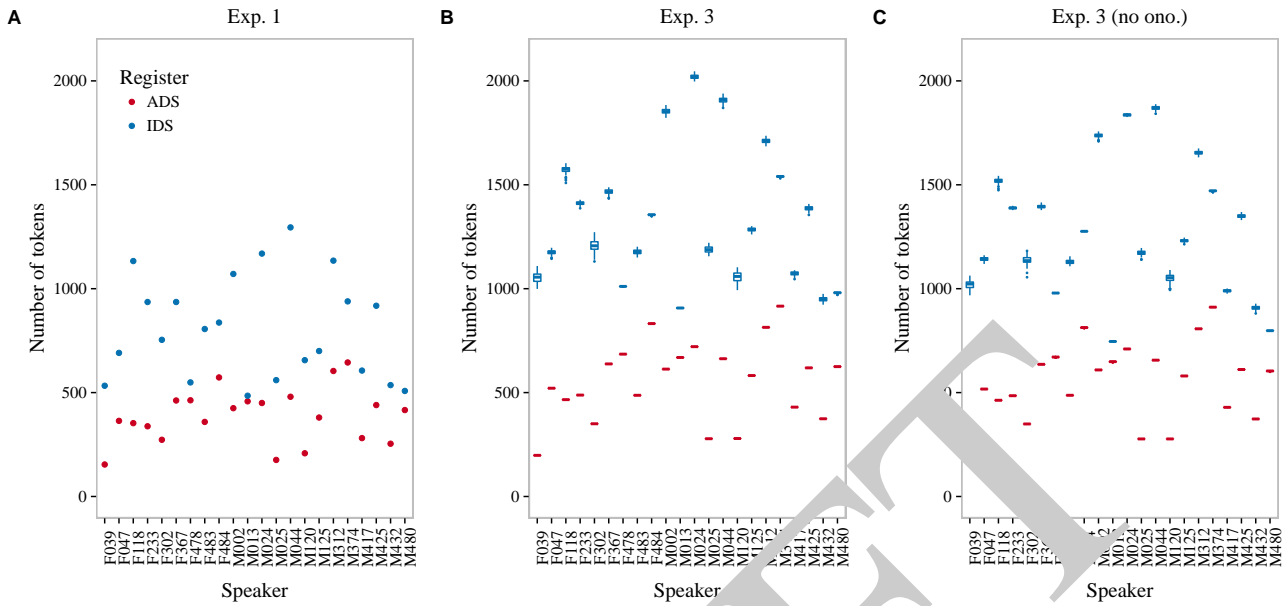


Figure A1. Total number of tokens used in Experiment 1 (A) and Experiment 3 with (B) and without (C) onomatopoeias, per speaker. ADS datapoints are shown as red, IDS datapoints in blue. For Experiment 3, boxplots show the distribution of number of tokens within the 100 sampled lexicons.

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