Lyman's Law can count only up to two*

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Abstract

One long-standing question that is recurrently addressed in contemporary phonological studies is whether phonological systems can count beyond two. The traditional view is that phonological systems can count only up to two but not more (e.g. Ito & Mester 2003; McCarthy & Prince 1986); some scholars, however, recently argue that phonological system should actually be able to count beyond two (e.g. Paster 2019; Kim 2020). The current experiments address this general question regarding counting by studying Rendaku and Lyman's Law in Japanese. Rendaku is a morphophonological process in which the morpheme-initial voiceless obstruent of a second member of a compound becomes voiced. The application probability of Rendaku is significantly reduced if the second member already contains a voiced obstruent, a generalization that is known as Lyman's Law. Experiment 1 compared the applicability of Rendaku in nonce words which contain one voiced obstruent (e.g. [ta**g**uta]) and those which contain two voiced obstruents (e.g. [te**g**e**b**i]). If Lyman's Law counts beyond two, Rendaku application is predicted to be more substantially reduced in the latter condition, as Rendaku would create morphemes which contains three voiced obstruents (i.e. [**d**e**g**e**b**i]). The results show, however, that no meaningful differences were observed between the two conditions. Experiment 2 tested the recent claim that two nasal consonants may reduce the applicability of Rendaku (Kim 2020; Kumagai 2017), which, if true, suggests that Lyman's Law disfavors a configuration in which a voiced obstruent is followed by two nasals. The results show that the evidence for the blockage of Rendaku by two nasals is weak or at best modest. Overall, we conclude that no strong evidence exists that Lyman's Law counts (Ito & Mester 2003).

Keywords: Rendaku, Lyman's Law, counting, experimental phonology, nasals, voicing
Approximate word count: 7500 words

*We would like to thank two anonymous reviewers and the associate editor as well as Arto Anttila, Canaan Breiss, Kaori Idemaru, Junko Ito, Yoonjung Kang, Haruo Kubozono and Armin Mester for their feedback. We also received useful comments and questions from the audience at AMP 2021 and a workshop accompanying the 29th Japanese/Korean Linguistics Conference. This project is supported by JSPS grants #22K00559 to Shigeto Kawahara and #19K13164 to Gakuji Kumagai. Remaining errors are ours.

1 Introduction

1.1 Theoretical background

One issue that is actively discussed in contemporary phonological studies is whether or not phonological systems can count only up to two. The predominant view in the generative literature has been that linguistic systems, including phonological systems, may count up to two but not more (e.g. Goldsmith 1976; Hewitt & Prince 1989; Ito & Mester 2003; McCarthy & Prince 1986; Myers 1997 among many others). This view is succinctly summarized by the following quote from McCarthy & Prince (1986: 1, quoted from the 1996 version):

> Consider first the role of counting in grammar. How long may a count run? General considerations of locality, now the common currency in all areas of linguistic thought, suggest that the answer is probably 'up to two': a rule may fix on one specified element and examine a structurally adjacent element and no other.

McCarthy & Prince (1986) claim for example that no reduplicative patterns copy three segments; i.e. [bad-badupi] vs. [bla-bladupi] vs. [adu-adupi]—they argue that this is a pattern that is predicted to arise if phonological systems can refer to three segments.

A similar view was reiterated by Ito & Mester (2003)—one of the main inspirations of the current study—who proposed to capture dissimilation effects in terms of local self-conjunction of markedness constraints (Smolensky 1995, 1997; see also Alderete 1997 and Blust 2012 for related proposals). In their view, a dissimilation force against two instances of the same structure [A] is modeled as resulting from a self-conjoined version of the markedness constraint prohibiting [A] within a particular domain, i.e. $*[A]\&*[A]_{domain}$. Since Ito & Mester (2003) take local conjunction to be a recursive operation, they raise the concern that the theory might predict a constraint prohibiting three instances of a particular structure. They doubt that this actually happens in the phonology of natural languages, stating that:

> With local conjunction as a recursive operation, ternary (and higher) conjunction such as (No-ϕ&$_\delta$No-ϕ)&$_\delta$No-ϕ = No-ϕ^2&$_\delta$No-ϕ = No-${\phi^3}_\delta$ are formally derivable. In the example given, the third violation of No-ϕ would be the fatal one. No convincing evidence has been found so far that No-ϕ^3 is ever linguistically operative separate from No-ϕ^2, which tends to support the old idea in generative linguistics (cf. syntactic movement theory) that the genuine contrast in grammars is not "1 vs. 2 vs. 3 vs. 4 vs. . . .", but "1 vs. greater than 1 (p.265)." [note by SK and GK: ϕ is a variable representing a phonological structure and δ is a variable representing a domain]

In other words, Ito and Mester (2003) argue that constraints that prohibit the co-occurrence of two tokens of the same segment/feature (="No-ϕ^2") are omnipresent in natural languages, but that constraints that prohibit the presence of three tokens (="No-ϕ^3") are unattested.

The hypothesis that phonology only counts up to two, however, was recently challenged by Paster (2019) in an article titled "Phonology counts." Paster (2019) argues, for example, that H-tones can spread twice (ternary H spreading), and likewise, H-tones can be displaced two moras to the right (ternary H displacement). In addition to these show-case examples, Paster (2019) adduces several other cases in which the phonological system apparently counts beyond two.

This question regarding whether phonological systems can count is also recently addressed in the context of counting cumulativity (Jäger 2007; Jäger & Rosenbach 2006), in which the numbers of constraint violations appear to additively affect phonological patterns. Some recent studies, in particular Hayes (2022), have proposed to take a linguistic scale—e.g. propensity to undergo vowel harmony in Hungarian—as a scale with actual numeric values and use these values to model various probabilistic phonological patterns (see also Breiss 2020; Kawahara 2020; McPherson & Hayes 2016; Smith & Pater 2020; Zuraw & Hayes 2017 for related proposals). In this view, linguistic systems can literally count the numbers of constraint violations and link those constraint violations to the predicted probabilities of the relevant output candidates. One widely used model to achieve this link is MaxEnt Harmonic Grammar (Goldwater & Johnson 2003; Hayes & Wilson 2008; Smolensky 1986), in which the numbers of weighted constraint violations are summed up to calculate the predicted probabilities of output candidates.[1]

Inspired by this debate, the current study addressed this general question about the (in)capability of counting by studying Rendaku and Lyman's Law in Japanese. Rendaku is a process in which the morpheme-initial voiceless obstruent of a second member of a compound becomes voiced. Lyman's Law reduces the applicability of Rendaku by prohibiting morphemes with two voiced obstruents (Ito & Mester 1986, 2003; Lyman 1894). Two experiments were conducted in order to explore whether Lyman's Law is able to count beyond two or not.

1.2 Background on Rendaku and Lyman's Law

The two experiments reported below make use of Rendaku and Lyman's Law to address the general question regarding the possibility of counting in phonological systems. In this subsection, we briefly review some background information on Rendaku and Lyman's Law. Rendaku is a morphophonological process in Japanese, in which the morpheme-initial obstruent of the second

[1] Noisy Harmonic Grammar (Boersma & Pater 2016) and Stochastic Optimality Theory (Boersma & Hayes 2001) have properties that are similar to MaxEnt, although they are still distinguishable (Flemming 2021; Zuraw & Hayes 2017).

element (henceforth, E2) in a compound undergoes voicing, as in (1).[2] Rendaku is blocked when E2 already contains a voiced obstruent, as in (2). The second generalization is known as Lyman's Law after Lyman (1894).

(1) Examples of Rendaku

a. /nise+**t**anuki/ → [nise+**d**anuki] 'fake raccoon'
b. /juki+**k**umi/ → [juki+**g**umi] 'Snow Team'
c. /hoɕi+**s**oɾa/ → [hoɕi+**z**oɾa] 'starry sky'
d. /oɕi+**h**ana/ → [oɕi+**b**ana] 'dried flower'

(2) Blocking of Rendaku by Lyman's Law

a. /ni+**t**ama**g**o/ → [ni+**t**ama**g**o], *[ni+**d**ama**g**o] 'boiled egg'
b. /çito+**k**a**g**e/ → [çito+**k**a**g**e], *[hito+**g**a**g**e] 'people's shadow'
c. /moɾi+**s**o**b**a/ → [moɾi+**s**o**b**a], *[moɾi+**z**o**b**a] 'cold soba'
d. /çito+**h**a**d**a/ → [çito+**h**a**d**a], *[hito+**b**a**d**a] 'people's skin'

Patterns of Rendaku are not as simple as the examples in (1) and (2) would appear to suggest, since various factors, both linguistic and idiosyncratic, affect the applicability of Rendaku (e.g. Kawahara 2015; Rosen 2016; Vance 2014, 2016, and especially Vance 2022). For example, for some items, the application of Rendaku is optional; e.g. both [kaɾa+seki] (without Rendaku) and [kaɾa+zeki] (with Rendaku) 'dry cough' are attested forms, and there is some non-negligible degree of inter-speaker variability as well (see especially Vance 2022: §7.7 and references cited therein). There are lexical items like [kemuɾi] 'smoke' and [saki] 'point', which never undergo Rendaku, despite the fact that there are no (known) reasons for them not to undergo Rendaku. There is thus a lot to be said about idiosyncratic properties of Rendaku.

However, one important aspect of Rendaku that we would like to highlight at this point is that there are also good reasons to consider it to be a (semi-productive) phonological pattern (Kawahara 2015). For example, it interacts with a phonological restriction such as OCP(labial), a constraint that prohibits two labial constraints in proximity, as well as with OCP(voice) (i.e. Lyman's Law), which prohibits two voiced obstruents within the same morpheme. See also Kobayashi et al. (2014) for evidence based on ERP patterns that Rendaku is a ruled-governed process.

Another aspect of Rendaku that we would like to make clear at this point is that when we run nonce word experiments on Rendaku, the results invariably show that Rendaku is semi-productive and that there is a rather large between-speaker variability (Kawahara 2012; Kawahara & Sano

[2] /h/ becomes [b] as a result of Rendaku, because historically /h/ was /p/ in Old Japanese (Vance 2015). [h] can arguably be considered to be underlyingly /p/ in the synchronic phonology of Modern Japanese as well (McCawley 1968, 124). This pairing of /h/∼[b] in the context of Rendaku does not crucially affect the rest of the discussion in this paper, however.

2014a; Vance 1979, 1980). Even when we use nonce words which do not contain any factor that would block Rendaku, not all speakers apply Rendaku 100% of the time, which is likely to be due to the fact that Rendaku is not fully productive in the contemporary Japanese, as we reviewed above. For instance, Kawahara and Sano (2014a) found that nonce words that do not violate Lyman's Law undergo Rendaku about 60% of the time on average. How often native speakers apply Rendaku to nonce words show some variation, and the source of such inter-speaker variability remains a mystery to date. This variation does not mean, however, that Rendaku is a random, unpredictable process: the influences of phonological factors—such as the effects of Lyman's Law and the avoidance of identical segments/moras—become clearly visible in nonce word experimentation, suggesting that Rendaku shows systematicity.

1.3 Direct motivations of the current study

Now moving on to the more direct motivations of the current study, in addition to the concern raised by Ito & Mester (2003), which is quoted above in §1.1, another study which directly motivated our current study is the recent claim about Rendaku and Lyman's Law, namely that two nasal consonants seem to block Rendaku. Kim (2020) has argued, based on the analysis of the Corpus of Spontaneous Japanese (Maekawa 2004), that no forms that contain two nasals (e.g. [hanami] 'cherry watching') undergo Rendaku. After excluding those forms whose Rendaku would be blocked for independent reasons, Kim (2020) found that there were 1,586 tokens and that about 40% of them showed Rendaku in that corpus. On the other hand, in the same corpus, there were 55 tokens which contain two nasals, and none of them underwent Rendaku.

Kumagai (2017) reports a nonce-word judgment study, which shows that nonce words which contain two nasals (e.g. [hanama]) were less likely to undergo Rendaku than those which contain just one nasal (e.g. [çimasa]). In that experiment, 133 native speakers of Japanese judged whether each nonce word should undergo Rendaku or not. The control condition showed about 60% of Rendaku application, whereas the target condition, in which /h/ was followed by two nasal consonants, showed only 43% of Rendaku application. These observations, if correct, imply that Japanese phonology disfavors a configuration in which a voiced obstruent is followed by two nasals, a statement which seems to require counting three segments (i.e. *[D…N…N]). Kim (2020) proposes a mechanism within a MaxEnt Harmonic Grammar in which the numbers of violations of Lyman's Law are scaled to account for the blocking of Rendaku by two nasals, assuming that nasals contribute to the violations of Lyman's Law. In short, this observation implies that Lyman's Law can count three segments. We thus aimed to examine this general possibility that Lyman's Law can count beyond two in further detail via experimentation.

2 Experiment 1

2.1 Introduction

Since whether nasals contribute to the violations of Lyman's Law is at best a controversial assumption (e.g. Ito & Mester 1986; Mester & Ito 1989; Rice 1993), Experiment 1 more directly addressed the possibility that a constraint can count three segments by testing whether Lyman's Law distinguishes words containing three voiced obstruents ([D. . . D. . . D]) from those containing two voiced obstruents ([D. . . D]), where "D" stands for a voiced obstruent. While Lyman's Law more or less categorically blocks Rendaku in real Japanese words (Vance 2015), the blockage of Rendaku by Lyman's Law is only probabilistic in nonce words (Vance 1979, 1980). Experiment 1 took advantage of this nature of Lyman's Law to address the question of counting in phonological systems.

To preview the results, we did not obtain strong evidence that Japanese speakers distinguish words containing three voiced obstruents ([D. . . D. . . D]) from those containing two voiced obstruents ([D. . . D]). In light of this result, Experiment 2 re-examined the claim that two nasals reduce the applicability of Rendaku (Kim 2020; Kumagai 2017).

2.2 Methods

For the sake of reproducibility (Winter 2019), the raw data, the R Markdown file and the Bayesian posterior samples are made available at an Open Science Framework (OSF) repository.[3] The Markdown file includes materials that are not reported in the paper, such as illustration of conditional effects and a posterior predictive check. Interested readers are welcome to examine these data, especially in ways that are not analyzed in this paper.

2.2.1 Overall design

The current experiment was a nonce-word judgment experiment on Rendaku, which consisted of three conditions: (1) nonce words with no voiced obstruent (e.g. [taruna]), (2) those with one voiced obstruent (e.g. [ta**g**uta]), and (3) those with two voiced obstruents (e.g. [te**g**u**b**i]). Existing native words in Japanese, the primary target of Rendaku, do not allow two voiced obstruents within a morpheme (Ito & Mester 1986, 2003), and thus we would not know from the behavior of existing words whether Lyman's Law distinguishes forms with one voiced obstruent and those with two voiced obstruents. Previous experimental studies of Rendaku and Lyman's Law also compared only nonce words with no voiced obstruents and those with one voiced obstruent (Kawahara 2012; Kawahara & Sano 2014a; Vance 1979, 1980), and thus whether Lyman's Law can count three

[3] `https://osf.io/9qgtx/`

segments has remained an open question till now. If Kim's (2020) MaxEnt-based proposal is on the right track, since the number of constraint violations are scaled up, we would expect Rendaku applicability to be lowest in the two voiced obstruent condition. On the other hand, the quote from Ito & Mester (2003) discussed above in §1.1 predicts that there should be no differences between the one voiced obstruent condition and the two voiced obstruent condition.

2.2.2 Stimuli

The list of nonce word E2s used in the current experiment is shown in Table 1. The experiment tested all four sounds that can potentially undergo Rendaku (=/t/, /k/, /s/ and /h/) with 6 nonce items each, resulting in 72 stimuli in total (3 voicing conditions * 4 consonants * 6 items). Some stimuli were adapted from previous studies of Rendaku using nonce words (Kawahara 2012; Kawahara & Sano 2014a; Vance 1979, 1980), as indicated by asterisks in Table 1.

None of these words becomes a real word when Rendaku is applied. All the stimuli consist of three light CV syllables (=three moras). In the one voiced obstruent condition, the voiced obstruent always appeared in the second syllable. Since it is known that Rendaku may be substantially inhibited when it results in identical CV mora sequences in E2 (Kawahara & Sano 2014b), care was taken so that Rendaku would not result in CV moras that are identical to those in the second syllables or to those in third syllables. In the second voiced obstruent condition, voiced obstruents appear in the second and third syllables.[4]

2.2.3 Participants

The experiment was distributed online using SurveyMonkey. The participants were primarily university students in Japan. Data were excluded if they reported either that (i) they were not a native speaker of Japanese, (ii) that they were not born in Japan, or (iii) that they knew Lyman's Law. Data from the remaining 149 participants entered into the following statistical analysis.[5]

2.2.4 Procedure

During the instructions, the participants were first told that when Japanese creates a compound, some combinations undergo voicing (i.e. Rendaku) while others do not. Three existing examples of

[4]Previous experiments have shown that there are no distance effects of Lyman's Law—voiced obstruents in the second syllable and those in the third syllables block Rendaku to a comparable degree in nonce word experimentation (Kawahara 2012; Kawahara & Sano 2014a, though see Vance 1979, 1980).

[5]We are grateful to Yuki Hirose for circulating this online experiment. As many as 40 participants reported that they knew Lyman's Law and were hence excluded, because the experiment was advertised among university students in Japan. Six participants were excluded because they were either non-native speakers or were not born in Japan. One participant was excluded because of failure to inform us whether Lyman's Law was known or not.

Table 1: The list of nonce words used as E2s in Experiment 1. Marked with an asterisk are the items that are directly adapted from Kawahara & Sano (2014a), who in turn adapted some stimuli from Kawahara (2012) and Vance (1979, 1980). /h/ is allophonically realized as [ç] before [i] and as [ɸ] before [u] (Vance 1987, 2008).

	0 vcd obs	1 vcd obs	2 vcd obs
/t/	[tamuma]*	[taguta]*	[tezuga]
	[tatsuka]*	[tozumi]*	[tezago]
	[taɾuna]*	[teguɾa]*	[tegubi]
	[tonime]*	[tazanu]	[taguga]
	[tekeha]*	[tegesa]	[tegoʑi]
	[tokeho]*	[toboɸu]	[tebigi]
/k/	[kimane]*	[kidaku]	[kidabe]
	[kikake]*	[kobono]*	[kodʑiba]
	[kotona]	[kabomo]*	[kaʑido]
	[kumise]	[kedeɾe]	[kudʑiba]
	[konihe]*	[kuʑiha]	[kezodo]
	[kehaɾo]*	[kozana]	[kadzuba]
/s/	[semaɾo]*	[sebaɾe]	[segabo]
	[sekato]*	[segeha]*	[sobogi]
	[sutane]*	[sobumo]*	[sugabi]
	[samohe]*	[sadanu]	[sobode]
	[soɾise]*	[sodoka]	[sadage]
	[sateme]*	[sudaɸu]	[sogebi]
/h/	[honaɾa]*	[hobasa]*	[hogada]
	[çinumi]*	[hazuke]	[hegazu]
	[honiko]*	[hogoɾe]*	[hedado]
	[hakisa]*	[çigiɾo]	[hadagu]
	[heɾaho]*	[ɸuzumo]	[çizuda]
	[çihonu]*	[hedeno]	[ɸubode]

Rendaku-undergoing forms and non-Rendaku-undergoing forms were used for illustration ([naga-gutsu] 'long boots', [suɾi-batɕi] 'grinding bowl', [ɸude-bako] 'pen case' and [aka-hoɴ] 'red book', [no-haɾa] 'field', [sanɕoku-sumiɾe] 'three-color violet'), but none of these examples involved a potential violation of Lyman's Law.

In the main session, the participants were instructed to take each stimulus item and combine it with [nise] "fake" as E1 to create a new compound. They were then asked whether the resulting compound would sound more natural with or without Rendaku; e.g. given a nonce word [taɾuna], when it is combined with [nise], which form sounds more natural, [nise-taɾuna] or [nise-daɾuna]? The stimuli were written in the *hiragana* orthography, which is used to represent native words in Japanese. Before the main session, the participants went through two practice trials with existing compounds. The stimuli in the main trial session were presented to the participants as nonce words.[6] The order of the stimuli in the main trial sessions was randomized per participant by SurveyMonkey.

2.2.5 Statistical analyses

The results were analyzed with a Bayesian mixed effects logistic regression model, using the `brms` package (Bürkner 2017). Bayesian analyses take prior information, if any, as well as the data at hand into consideration, to produce a range of possible values (i.e. posterior distributions) for each estimated parameter (for those readers who are unfamiliar with Bayesian analyses, there are now a number of accessible introductions to Bayesian modeling: e.g. Franke & Roettger 2019; Kruschke 2014; Kruschke & Liddell 2018). Unlike a more traditional frequentist analysis, we can interpret these posterior distributions as directly reflecting the likely values of these estimates.[7] As a useful inference heuristic, we can examine the middle 95% of the posterior distribution, known as 95% Credible Interval (henceforth, 95% CrI) —if that interval does not include 0, then we can interpret that effect to be meaningful. If it includes 0, then we can examine its posterior distribution more carefully to determine with how much certainty we can conclude the null effect. This ability to be able to test null effects is one advantage of Bayesian analyses, which we used in the interpretations of our results, over frequentist analyses (Gallistel 2009). See §2.3 below for further details on the test of null effects within a Bayesian framework.

For the current statistical model, the dependent variable was whether each item was judged to undergo Rendaku or not (*yes Rendaku* = 1 vs. *no Rendaku* = 0). The main fixed factor was the number of voiced obstruents contained in E2. The reference level was set to be the condition with one voiced obstruent, so that we can make each pairwise comparison between the three voicing conditions. Another fixed factor was sound type (i.e. /t/-/k/-/s/-/h/) in order to examine how general the effects of voiced obstruents, if any, would hold. The interaction term between the two factors was also coded. A random intercept of items and participants as well as random slopes of participants for both of the fixed factors and their interaction were included. In general, Bayesian models are less likely to face convergence issues than frequentist generalized linear mixed effects models, thus allowing us to fit a model with a random structure that is as complex as the current model (e.g. Eager & Joseph 2017).

[6] Kawahara (2012) tested whether presenting the stimuli as nonce words or presenting them as obsolete native words (as done by Vance 1979, 1980; Zuraw 2000) would impact the Japanese speakers' judgment on Rendaku. Since no substantial differences were found between these experimental formats, we deployed the first format in the current experiment. The stimuli, however, were presented in the *hiragana* orthography, which is used to represent native words.

[7] People often interpret 95% confidence intervals calculated in a frequentist analysis as if they directly reflect the uncertainty about the estimates (i.e. the ranges of possible values that the estimates can take), but this is a misinterpretation (e.g. Kruschke & Liddell 2018).

Four chains with 3,000 iterations were run, and the first 1,000 iterations from each chain were discarded as warmups. We used the following prior specifications: a Normal(0, 1) weakly informative prior for the intercept (Lemoine 2019) and a Cauchy prior with scale of 2.5 for all slope coefficients (Gelman et al. 2018). All the $\hat{R}$-values for the fixed effects were 1.00 and there were no divergent transitions, indicating that the chains mixed successfully. See the R Markdown file for complete details.

2.3 Results

Figure 1 shows the Rendaku application rate for each condition in the form of violin plots, whose width represent normalized probability distributions of the responses. Each panel shows a different segment type. Within each panel, each violin shows the three conditions with different numbers of voiced obstruents (0, 1, 2 from left to right). Transparent circles show averaged responses from each participant. Solid red circles represent grand averages. Abstracting away from segmental differences, the three voicing conditions resulted in the following Rendaku application rates: (1) 57.8%, (2) 30.8%, (3) 33.0%.[8]

[8] After the experiment, we realized that some of the forms in the 0 voiced obstruent condition that we adapted from the previous studies contained two nasals, which may undergo Rendaku less often. Inclusion of such items, however, is conservative in the sense that it can reduce—rather than enhance—the Rendaku applicability in the condition where Lyman's Law is not relevant. A post-hoc analysis compared those four items that include two nasals ([tamuma], [tonime], [kimane], and [çinumi]) and the rest of the items in the first condition; we found that the former forms were slightly less likely to undergo Rendaku than the latter (55.4% vs. 58.3%). Since this is a post-hoc comparison, we did not attempt to conduct statistical comparisons (see Kerr 1998; Simmons et al. 2011 for a potential danger of running statistical tests after seeing the results). Instead, Experiment 2 reported below explored this difference in a more systematic way.

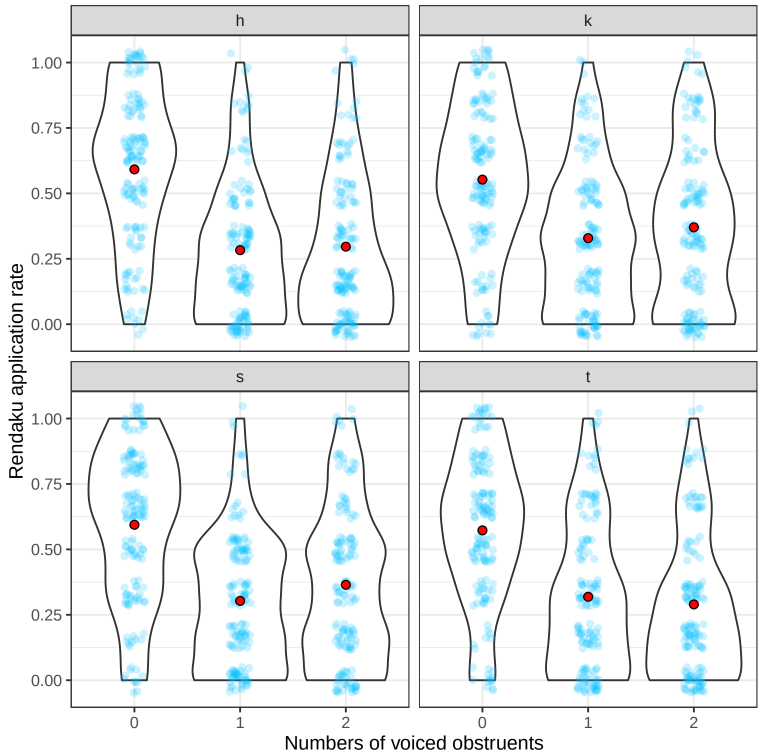

Figure 1: The results of Experiment 1.

We observe that the first condition (no violations of Lyman's Law) differs from the second and the third conditions (violations of Lyman's Law). This overall result is in line with previous experimental studies of Rendaku and Lyman's Law, providing further support for the psychological reality of Lyman's Law (Kawahara 2012; Kawahara & Sano 2014a; Vance 1979, 1980). On the other hand, no apparent differences were observed between the second and the third conditions—Rendaku was no less likely to be observed if it resulted in three voiced obstruents compared to when it resulted in two voiced obstruents. If anything, the third condition overall showed higher Rendaku rate than the second condition. This result is compatible with the formulation of Lyman's Law by Ito & Mester (2003), but not with a general idea advanced by Kim (2020) (though we hasten to add at this point that Kim's claim is not based on the number of voiced obstruents).

The model summary of the Bayesian mixed effects logistic regression analysis appears in Table 2. For the sound type (=the coefficients in (b)), /h/ serves as the baseline. All of the relevant 95% CrIs for the coefficients in (b) include 0, suggesting that differences among the four segment types were not very meaningful, although /t/ and /k/ were slightly more likely to undergo Rendaku compared to /h/. None of the interaction terms (=the coefficients in (d)) appear to be meaningful either, suggesting that the effects of voiced obstruents do not differ substantially among different consonant types, though the first interaction term shows that the effects of Lyman's Law were slightly less pronounced for /k/ than for /h/.

More relevant to the main aim of the experiment are the effects of voiced obstruents (=the coefficients in (c)). The difference between the no voiced obstruent condition and the one voiced obstruent condition is highly meaningful, suggesting that Lyman's Law reduced Rendaku applicability. In fact, all the posterior samples for this β-coefficient were positive ($p(\beta > 0) = 0$). The difference between the one voiced obstruent and the two voiced obstruent condition does not seem credible, however. For this comparison, we examined what proportion of posterior samples were negative, because if anything, we expected that Rendaku might be less likely to apply when it resulted in three voiced obstruents (*à la* Kim 2020 and Kumagai 2017). Only 49% of the posterior samples of this β-coefficient were negative ($p(\beta < 0) = 0.49$).

Table 2: Summary of the Bayesian mixed effects logistic regression model (Experiment 1).

		β	error	95% CrI
(a) intercept		-1.20	0.20	[-1.61, -0.80]
(b) sound type	/k/	0.26	0.25	[-0.23, 0.75]
	/s/	0.09	0.26	[-0.42, 0.59]
	/t/	0.17	0.25	[-0.32, 0.67]
(c) vcd obs	0 vs. 1	1.64	0.27	[1.11, 2.17]
	2 vs. 1	0.00	0.25	[-0.48, 0.49]
(d) interactions	/k/:0 vs. 1	-0.45	0.35	[-1.12, 0.23]
	/s/:0 vs. 1	-0.05	0.35	[-0.74, 0.66]
	/t/:0 vs. 1	-0.25	0.35	[-0.94, 0.44]
	/k/:2 vs. 1	0.16	0.35	[-0.54, 0.84]
	/s/:2 vs. 1	0.31	0.35	[-0.37, 1.00]
	/t/:2 vs. 1	-0.26	0.35	[-0.94, 0.44]

Since the difference between the one voiced obstruent and the two voiced obstruent condition was not apparent, we took advantage of a Bayesian analysis to explore to what extent we can believe in "the null effect" for this difference. To do so, we deployed an analysis using ROPE (Region of Practical Equivalence: Kruschke & Liddell 2018; Makowski et al. 2019). The basic idea is that we define a range that is equivalent to a point estimate—here $\beta = 0$—and examine how many posterior samples are contained in that region, a region that can be considered to be equivalent to 0 for practical purposes. Following Makowski et al. (2019), we take 0.1—a negligible effect size according to Cohen (1988)—of a standardized parameter to define that ROPE. In logistic regression models, this ROPE ranges from [-0.18, 0.18]. We used `bayestestR` (Makowski et al. 2020) to calculate how many posterior samples are contained in this ROPE. This analysis shows that 55.8% of the posterior samples within the 95% Credible Intervals were contained in this ROPE. In other words, we can be about 56% certain that there are no differences between the two conditions.

Finally, the associate editor pointed out that there seems to be some substantial between-speaker variability in Figure 1. Such inter-speaker variability was to be expected given that Rendaku shows some between-speaker variability in the real words, and that such variation has been observed in previous nonce-word experiments, starting with the seminal experimental work by Vance (1979, 1980) (see §1.2). To further explore the patterns of inter-speaker variation in the current experiment, Figure 2 compares the first condition and the second condition (the left panel) and the second condition and the third condition (the right panel) for each speaker. Each dot represents the Rendaku applicability rate for each speaker. In the left panel, we observe that most if not all dots are below the diagonal axis, suggesting that most speakers applied Rendaku more often when it does not violate Lyman's Law, again supporting the psychological reality of Lyman's Law. The right panel shows that there is no clear systematicity with respect to whether Rendaku is more likely to apply when it results in two voiced obstruents or three voiced obstruents.

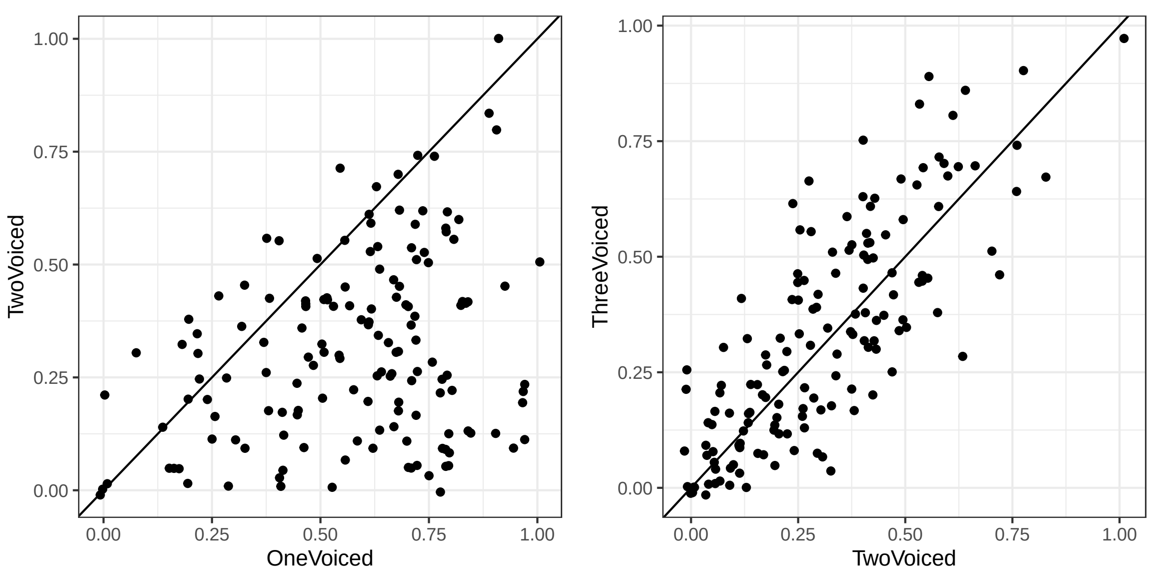

Figure 2: Comparing the Rendaku application rate of the different conditions for each speaker in Experiment 1. Each dot represents each speaker, which are slightly jittered for the sake of illustration.

2.4 Discussion

The specific question we addressed in Experiment 1 is whether or not Lyman's Law counts the number of voiced obstruents, i.e. whether it distinguishes forms with two voiced obstruents from those with three voiced obstruents. A short answer is that it apparently does not. While we were unable to prove "the null effect," no convincing evidence was obtained that Lyman's Law counts beyond two. The results are compatible with the remark by Ito & Mester (2003) which we quoted in §1.1, as well as the general view reviewed in that section that phonological systems do not count beyond two (Goldsmith 1976; Hewitt & Prince 1989; Ito & Mester 2003; McCarthy & Prince 1986; Myers 1997).

From the perspective of Optimality Theory (Prince & Smolensky 1993/2004), we can interpret the current results as suggesting that, regardless of whether a morpheme contains two voiced obstruents or three voiced obstruents, the constraint behind Lyman's Law is violated to an equal degree. For example, this constraint can assign a violation mark for every morpheme that contains more than one voiced obstruent, rather than assigning a violation mark for each pair of voiced obstruents. The latter formulation is assumed by Kim (2020) and Ito & Mester (2003), the latter of whom state that "[f]or $C_1\&_\delta C_1$, the special case of self-conjunction with $C_1 = C_2$, this implies that a candidate receives a violation mark for **each pair** of violation marks ($*C_1$, $*C_1$) it has accrued for C_1 in domain δ" (p.23, emphasis ours). The current experiment seems to suggest that instead, it is a domain (i.e. morpheme) that receive a violation mark in this case. This is compatible with the definition of local conjunction that Moreton & Smolensky (2002) give: "*the local conjunction of C_1 and C_2 in D*, is a constraint which is violated whenever there is a domain of type D in which both C_1 and C_2 are violated" (p.306, emphasis in the original).

At this point, we note that our study is specifically about how Lyman's Law behaves with respect to the number of voiced obstruents—it may as well be the case that Lyman's Law counts only up to two, but that other phonological systems are able to count beyond two (Paster 2019). We will come back to this general issue in the conclusion section.

A question that arises given the current results is how we should reconcile the current results with one of the direct motivations of the current study—the observation that two nasals seem to block Rendaku (Kim 2020; Kumagai 2017). One possibility is that this observation was actually epiphenomenal. Inspection of the actual examples used by Kim (2020) shows that many of the E2s are actually compounds.[9] For example, [hanami] "cherry watching" consists of [hana] "flower/cherry" and [mi] "watching." Other examples of this kind include [kami-no-ke] '(lit.) head's hair' and [tate-mono] '(lit.) built things.' Since it is independently known that Rendaku applies only to the elements on right branches of compounds (Ito & Mester 1986; Otsu 1980), these examples may be explained away in terms of this independently motivated restriction. Other examples include those complex E2s whose left member already contain a voiced obstruent (e.g. [tabe-mono] 'food' and [hidari-mimi] 'left ear'), and Rendaku in such examples should be blocked by that voiced obstruent, not necessarily by the two nasals. Some other items included in Kim's (2020) data are actually those that can undergo Rendaku (e.g. [konomi] 'favorite' vs. [jori-**g**onomi] 'pick

[9]We are grateful to Seoyoung Kim for sharing her raw data. See Kim (2022) for a renewed analysis of the two nasal effect using the Rendaku database (Irwin et al. 2020). See also Kawahara & Kumagai (2022) for a detailed reexamination of this reanalysis presented in Kim (2022).

and choose' and [tanomi] 'plea' vs. [kami-**d**anomi] 'plea to a god'), although non-Rendaku forms may have appeared in the corpus.

These alternative explanations, however, do not provide an explanation for the experimental finding by Kumagai (2017), because that experiment made use of monomorphemic nonce words as E2s. One issue that can be raised about the experiment by Kumagai (2017), however, is that it had only three items for each condition, and thus the generalizability of his findings can be questioned. In light of the results of Experiment 1, we feel that it is necessary to reexamine Kumagai's (2017) experimental finding by expanding the number of items tested. Experiment 2 takes up on this task.

3 Experiment 2

3.1 Introduction

Experiment 1 found that two voiced obstruents and three voiced obstruents are treated alike for the calculation of Lyman's Law, which means Lyman's Law seems to count only up to two. Given this result, the next experiment was designed to re-examine the claim that two nasal consonants may trigger Lyman's Law and inhibit Rendaku (Kim 2020; Kumagai 2017). Recall that many examples used by Kim (2020) can potentially be explained away in terms of other independently motivated restrictions on Rendaku, and that Kumagai's (2017) experiment had only three items for each condition.

There are independent reasons to test—more robustly than Kumagai (2017) did—the possibility that two nasals can block Rendaku in Japanese. Specifically, the [voice] specifications of sonorant consonants in Japanese have been known to be ambivalent. On the one hand, the standard view about the role of sonorants in triggering Lyman's Law is that they do not, and there have been several attempts to model this observation. The inertness of sonorant voicing with respect to Lyman's Law has been modeled by using the underspecification theory (Ito & Mester 1986), by positing a privative [voice] feature that is specific to obstruents (Mester & Ito 1989), or by positing different [voice] features for sonorants and obstruents (Rice 1993). See Kawahara & Zamma (2016) for a review of these proposals.

On the other hand, there is some evidence that sonorants, especially nasals, are specified for [voice] in Japanese phonology. The clearest evidence comes from the fact that nasals trigger voicing of following voiceless consonants, as observed in the past tense formation (e.g. /kam-ta/ $\rightarrow$ [kan-da] 'bite + PAST'), which seems to suggest that moraic nasals in Japanese are specified for [+voice] (Ito et al. 1995; Rice 1993).[10] An analysis of half rhymes in Japanese rap lyrics like-

[10]We should also note that the productivity of alternation patterns observed in verbal inflection paradigms has been questioned by several nonce word experiments (Vance 1987, 1991). Hayashi & Iverson (1998) also argue that post-nasal voicing in Japanese is non-assimilative in nature, and thus does not offer evidence that nasals are specified as

wise shows that sonorant consonants are more likely to rhyme with voiced obstruents than with voiceless obstruents (Kawahara 2007), and the same generalization holds in the pairing patterns of imperfect puns (Kawahara & Shinohara 2009), although these studies argue that these pairing patterns are based on perceptual similarity rather than phonological similarity. In short, there are some ways in which nasals—and perhaps sonorants in general—could be interpreted as being specified as [+voice] in Japanese, and it would be interesting to test whether this feature can trigger Lyman's Law, especially when there are two instances of nasals/sonorants.

3.2 Methods

As with Experiment 1, the raw data, the R Markdown file, and the Bayesian posterior samples are available at the OSF repository.

3.2.1 Stimuli

In order to test whether two nasals can trigger Lyman's Law, this experiment compared nonce words which contained different numbers of nasals. The experiment also tested whether two instances of other sonorant consonants would trigger Lyman's Law, because the ambivalent nature of [voice] specification pertains to all sonorant types (cf. Ito et al. 1995). In order to keep the size of the overall experiment manageable, we limited ourselves to those items that begin with [h].[11] The first condition, which served as a baseline condition, had a voiceless obstruent in the second and third syllables (=condition (a)). The second condition had a nasal in the second syllable and a voiceless obstruent in the third syllable (=condition (b))—this condition was included to experimentally test the assumption embraced in the theoretical literature reviewed above that one nasal does not block Rendaku. The third condition is a critical condition, which contained two nasals, one in the second syllable and one in the third syllable.

We also included items which include one [ɾ] in the second syllable (=condition (d)) and those items which include two [ɾ]s (=condition (e)), as well as those which include one approximant/glide

[+voice] in Japanese phonology.

An associate editor also notes that post-nasal voicing is observed in many languages (Riehl 2008), and that for some languages like English at least, this voicing effect should be considered as a matter of phonetic implementation rather than a categorical phonological process (Davidson 2016; Hayes & Stivers 1995). For the case of Japanese, however, post-nasal voicing manifests itself as affecting how the past tense morpheme is produced (to the extent that this is a productive pattern). Post-nasal voicing is also observed as a phonotactic restriction in that no native words contain a voiceless obstruent after a nasal consonant. Thus, there are some reasons to consider post-nasal voicing in Japanese to be phonological rather than phonetic (Ito & Mester 1995).

[11] A practical consideration that entered into this decision is so that we could use the Buy Response function in SurveyMonkey (see below), given that with Experiment 1, we had more or less used up our pool of participants whose data we can use for experiments related to Rendaku. The Buy Response function, however, allows us to include only up to 50 questions. Kawahara & Kumagai (2022) reports a similar experiment on the effects of two nasals which used all the segments that can potentially undergo Rendaku.

Table 3: The list of nonce words used in Experiment 2.

(a) [h-vls-vls]	(b) [h-nas-vls]	(c) [h-nas-nas]	
[hatosa]	[hanuta]	[hanumo]	
[hasaka]	[hanasa]	[hanama]	
[hetosa]	[henoke]	[henona]	
[hekita]	[henaso]	[henema]	
[hotaso]	[honato]	[honimu]	
[hokata]	[honika]	[honine]	
(d) [h-ɾ-vls]	(e) [h-ɾ-ɾ]	(f) [h-App-vls]	(g) [h-App-App]
[haɾito]	[haɾuɾa]	[hajuto]	[hajuwa]
[haɾose]	[haɾaɾe]	[hawase]	[hawaja]
[heɾota]	[heɾoɾa]	[hejata]	[hejowa]
[heɾesa]	[heɾeɾa]	[hewasa]	[hewaja]
[hoɾike]	[hoɾiɾu]	[hojaso]	[hojuwa]
[hoɾiso]	[hoɾiɾo]	[howake]	[howaju]

(=condition (f)) and those which include two approximants (=condition (g)). These conditions allowed us to explore whether it is only two nasals that can block Rendaku, or whether other sonorants can behave similarly when there are two of them.

The actual list of stimuli appears in Table 3. Just as in Experiment 1, no items were existing words as they were, nor after they underwent Rendaku. They were all trisyllabic with three open syllables.

3.2.2 Participants

A total of 133 participants were recruited using the Buy Response function offered by SurveyMonkey. Data from one participant was excluded because of being a non-native speaker of Japanese. Data from additional 11 native speakers were obtained from a Japanese university, resulting in a total of responses from 143 speakers. The procedure was identical to that of Experiment 1. Each participant was assigned a uniquely randomized order of the stimuli.

3.2.3 Statistics

As with Experiment 1, the data was analyzed using a Bayesian mixed effects logistic regression model. The fixed variable was the 7-level condition which coded the phonological differences listed in Table 3. The baseline was set to be the condition (a), forms in which /h/ was followed by two voiceless obstruents. The model also included free-varying random intercepts for items and participants as well as the random slope for participants for the fixed effect. The prior specifications were identical to those that were used for Experiment 1. Four chains with 3,000 iterations were run with 1,000 warm-ups. All the $\hat{R}$-values for the fixed factors were 1 and there were no divergent transitions, suggesting that the four chains mixed successfully.

3.3 Results

Figure 3 shows the Rendaku application rate for each condition in the form of violin plots, whose width represent normalized probability distributions. Transparent circles show averaged responses from each participant. Solid red circles represent grand averages. The seven phonological conditions resulted in the following Rendaku application rates: (a) [h-vls-vls]= 43.6%; (b) [h-nas-vls] = 43.8%; (c) [h-nas-nas] = 40.2%; (d) [h-ɾ-vls] = 45.0%; (e) [h-ɾ-ɾ] = 44.9%; (f) [h -App-vls] = 43.5%; (g) [h-App-App] = 38.0%.

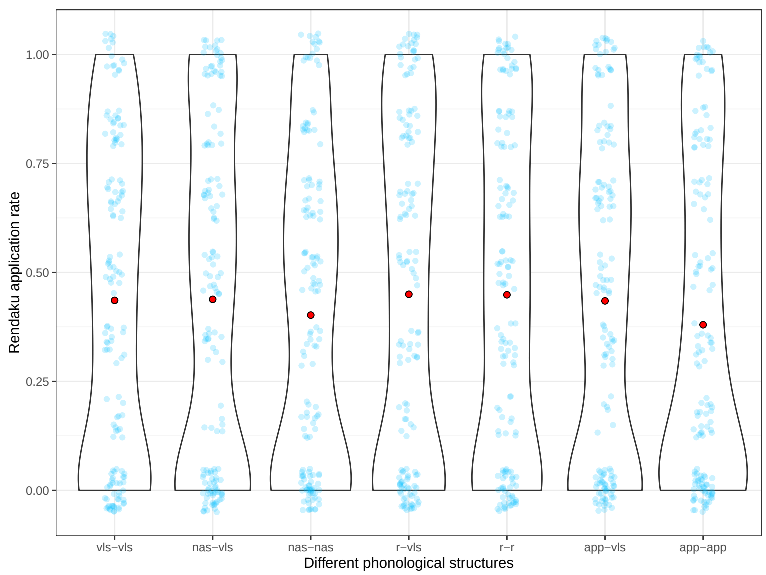

Figure 3: The results of Experiment 2.

Overall, the effects of phonological compositions of the stimuli were not very apparent.[12] The critical condition, which contained two nasal consonants, showed 3.4% reduction in Rendaku responses compared to the baseline condition. The conditions which contained one sonorant,

[12] It is interesting that in this experiment, E2 which does not contain any items that would trigger Lyman's Law generally show the rate of rendaku application (38.0%-45.0%) which is well below the 0 voiced obstruent condition in Experiment 1 (57.8%). We honestly did not expect this difference, and do not have a good explanation for it. One possibility is that this difference could be an unintentional consequence of participants not wanting to have too many positive Rendaku responses overall (recall that there was no condition which involved a clear violation of Lyman's Law—those Es with a voiced obstruent—in this experiment). Kawahara & Kumagai (2022) report an experiment which more directly compared forms with two voiced obstruents which would clearly Lyman's Law and those that contain two nasals.

whether it were a nasal, [ɾ], or an approximant, did not show any substantial reduction in Rendaku responses. The clearest case was the stimuli with two approximants, which showed the reduction in Rendaku responses by 5.6% compared to the baseline condition.

The model summary of a Bayesian mixed effects model is shown in Table 4. As observed in the table, the condition with two approximants is the only condition whose 95% CrI does not include 0. Since we did observe some reduction in Rendaku applicability for the condition with two nasals, we calculated the proportions of posterior samples that are negative for this β-coefficient, and found that 90.6% of them were negative. If we take the conservative measure and assume that the lower edge of the ROPE (i.e. -0.18) should define the critical region, then only 64.9% of the posterior samples are below -0.18. This result suggests that we can only be 65% confident that two nasals lower Rendaku responses to a non-negligible degree. We conclude that the evidence for the probabilistic blocking of Rendaku by two nasals is weak or at best moderate.[13] We can also conclude that there is no strong evidence that [+voice] feature of nasals, to the extent that Japanese nasal consonants are specified as such, trigger Lyman's Law either, regardless of whether nasals occur once or twice.

Table 4: Summary of the Bayesian mixed effects logistic regression model (Experiment 2).

		β	error	95% CrI
(a) intercept		-0.82	0.31	[-1.44, -0.20]
(b) condition	nas-vls	-0.01	0.20	[-0.41, 0.38]
	nas-nas	-0.25	0.19	[-0.63, 0.13]
	ɾ-vls	0.10	0.20	[-0.28, 0.49]
	ɾ-ɾ	0.11	0.19	[-0.26, 0.50]
	app-vls	-0.01	0.20	[-0.40, 0.38]
	app-app	-0.47	0.21	[-0.89, -0.04]

As with Experiment 1, we observe some inter-speaker variability, and thus Figure 4 compares the control condition (forms with two voiceless obstruents) and the two nasal condition. There does not seem to be systematic patterns which suggest a clear difference between the two conditions.

[13] See also Kawahara & Kumagai 2022 for a follow-up study with a larger number items and participants, which showed the opposite trend, in which forms with two nasals showed slightly higher, rather than lower, Rendaku response rates than the control condition, although that trend was not credible. This result offers an additional reason to believe that the effects of two nasal consonants are suspicious.

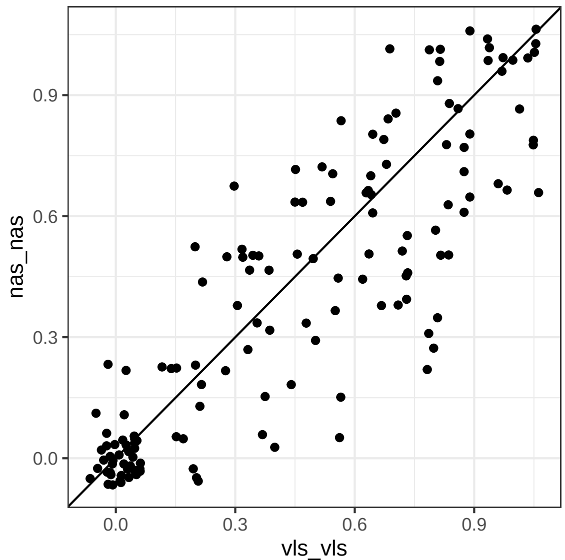

Figure 4: The comparison between the control condition and the two nasal condition by each speaker.

3.4 Discussion

This experiment was set out to re-examine the previous claim that two nasals may block Rendaku. The results show however that the evidence for this blockage effect was weak or at best moderate. Comparing the current results with those of Kumagai (2017), the crucial items used in the latter experiment were [hanama], [çinama] and [ɸunama], which all end with [nama]. The current stimuli contained [hanama], and therefore, as a post-hoc comparison, we compared [hanama] and other items. Indeed, [hanama] showed slightly lower Rendaku responses than other items in the same condition: 38.5% vs. 40.6%. The blockage of Rendaku may have something to do with that specific [nama] sequence, but does not seem to generalize to other items containing two nasals.

On the other hand, the condition with two approximants showed reduction in Rendaku rates to a degree which can be considered to be credible. We find this result puzzling. We know of no good reason why approximants, to the exclusion of nasals or [ɾ]s, interact with a voiced obstruent in the calculation of Lyman's Law in Japanese phonology. If anything, the [voice] specification is more clearly motivated for nasals than for approximants, as the former arguably triggers post-nasal voicing in Japanese (Ito et al. 1995, though see Hayashi & Iverson 1998 and Vance 1991).

4 Conclusion

The two experiments reported above did not find convincing evidence that Lyman's Law counts. How should we interpret the current results in light of the recent proposal by Paster (2019) that phonological systems can count? While Paster (2019) shows several pieces of evidence that phonology can apparently count, she also points out that all of these patterns that apparently count are related to tones and stress, and the counting behavior does not seem to be observed for patterns related to segmental phonology. The claim by Kim (2020) and Kumagai (2017) would have been a counterexample to this generalization by Paster (2019), but this claim did not replicate well in the current experiment.[14] There may be, therefore, an important distinction to be made between segmental phonological patterns and suprasegmental phonological patterns, only the latter of which can count.[15] More experimental evidence is called for to establish the thesis that segmental phonological patterns never count beyond two, however. See Hyman (2011), Jardine (2016), McPherson (2020), Pater (2018) among others for different views on this distinction between segmental phonology and suprasegmental phonology.

The next question is how we should interpret the current results in the context of the recent success of MaxEnt Harmonic Grammar in modeling various probabilistic phonological patterns. In this theory, the number of constraint violations are counted, multiplied by the constraint weights, and the resulting numerical values are mapped onto predicted probabilities of the candidates (Breiss 2020; Hayes 2022; Kawahara 2020; McPherson & Hayes 2016; Smith & Pater 2020; Zuraw & Hayes 2017). To the extent that we accept the thesis that phonological systems can count the number of violations, it seems to us that the logical conclusion is that Lyman's Law assigns a violation mark to each morpheme, but not each pair of voiced consonants (Moreton & Smolensky 2002, c.f. Ito & Mester 2003 and Kim 2020). More generally speaking, constraints cannot assign a violation mark based on a structural description that involves more than two segments, although the grammar may count the number of constraint violations. The emerging hypothesis is that constraint violations can be counted (as in MaxEnt Harmonic Grammar), but constraints themselves cannot count the number of segments (as in the current experimental results). This new hypothesis

[14] Setting aside the puzzling effect of two approximants.

[15] In addition to cases that Paster (2019) discusses, cases of a three-way length contrast—whether they are consonantal contrasts or vocalic contrasts—may be another example of counting (i.e. 0 mora vs. 1 mora vs. 2 moras) in suprasegmental phonology. For descriptions and analyses of such three-way contrasts, see Bals Baal et al. 2012, Hoogshagen 1959, Prince 1980, Thomas & Shaterian 1990 and Remijsen & Gilley 2008

Also, there may even be evidence from Japanese phonology that suprasegmental phonological patterns can count beyond two. The accentuation patterns of compound nouns in Tokyo Japanese show a three-way distinction: those with a *short* (one foot) second member, those with a *long* second member (two feet), and those with an *overlong* second member (three feet or longer) (see e.g. Kubozono et al. 1997; Poser 1990). Similarly, the accent pattern of *X-jiroo* compounds shows a tripartite distinction depending on the length of the first element; whether it is (a) monomoraic (*ko-jiroo*, unaccented), (b) bimoraic (*ki'n-jiroo*, initial accent) or (c) longer (*tikara-ji'roo*, accent on *jiroo*) (Kubozono 1999).

should be tested against a wider range of phonological phenomena across different languages.

To conclude, we started with a rather general question in phonological theorization—does phonology count? We addressed this question by exploring whether Lyman's Law counts beyond two or not. In Experiment 1, we addressed the question whether Lyman's Law distinguishes morphemes with two voiced obstruents and those with three voiced obstruents. The results show that there is no strong evidence for such counting behavior. In light of this negative result, we re-examined the direct motivation of Experiment 1—the recent claim that two nasals may reduce Rendaku applicability. Experiment 2 expanded upon Kumagai (2017) and included more items per each phonological condition. The results provided at best modest evidence for the counting behavior. The general conclusion that we can draw from these results is that it is unlikely that Lyman's Law counts, except for the puzzling behavior of two glides, which itself requires further scrutiny.

Funding

Supported by JSPS grants #22K00559 to the first author and #19K13164 to the second author.

Conflicts of interest

The authors declare no conflicts of interest.

Availability of data and material

The data are available at
`https://osf.io/9qgtx/`

Code availability (software application or custom code)

The code is available at
`https://osf.io/9qgtx/`

Authors' contributions

Both authors contributed to the conception and execution of the experiments. The first author wrote the manuscript and the second author revised it. The statistical analysis was primarily conducted by the first author. The second author checked the details. Both authors contributed to revising the manuscript.

Ethics approval

The current experiment was conducted with an approval from the authors' institute.

Consent to participate

The participants read through the consent form before participating in the experiments.

Consent for publication

Both authors approve that the current manuscript be evaluated for publication in the journal.

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