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The nonlocal nature of Lyman's Law revisited

Shigeto Kawahara*, The Institute of Cultural and Linguistic Studies at Keio University, Japan; International Christian University, Japan, kawahara@icl.keio.ac.jp

Gakuji Kumagai, Department of English Language and Literature, Faculty of Letters, Kansai University, Japan, gakuji1210@yahoo.co.jp

*Corresponding author.

Past studies (Vance, 1979; Kawahara, 2012) of rendaku, a morphonological alternation in Japanese, have produced conflicting results about the sensitivity of Lyman's Law to a locality effect in nonce words. In a large-scale forced-choice experiment with 72 stimuli, our analysis of the responses from 180 native speakers of Japanese shows that for many speakers, Lyman's Law is indeed sensitive to a locality effect: in nonce words, the blockage effect of rendaku by Lyman's Law tends to be stronger when the blocker consonant is in the second syllable than when it is in the third syllable. This finding supports Vance's original insight. Then, to explore why Kawahara's study failed to find a locality effect, we replicated it with a larger number of speakers, and found some evidence that the locality effect is identifiable in a naturalness judgment experiment as well.

1. Introduction

Dissimilation effects are often sensitive to a distance-and-decay effect: i.e., dissimilative forces are stronger between two closer segments (see Suzuki, 1998, for a review; see also Bennett, 2015; Hansson, 2001, for other extensive typological studies of dissimilation). For example, in Yimas, rhotic dissimilation applies only when two rhotics are in the adjacent syllables, but not when they are farther apart (Foley, 1991, cited by Suzuki, 1998). A well-known case of similarity-based phonotactic restrictions in Arabic is also more stringent between two adjacent consonants than between two nonadjacent consonants (Frisch et al., 2004). Against this cross-linguistic observation, this paper tests whether Lyman's Law in Japanese—a dissimilation constraint against two voiced obstruents within a morpheme—is stronger between two local consonants than between two nonlocal consonants, since the past results on this question have been mixed.

Lyman's Law most clearly manifests itself in the blockage of rendaku.[1] Rendaku is a morphophonological alternation process, in which the morpheme-initial obstruent of the second element (henceforth *E2*) in a compound undergoes voicing, as in (1) (/h/ surfaces as [b] as a result of voicing, since /h/ in Japanese was historically—or is arguably underlyingly—/p/: McCawley, 1968). Rendaku, however, is blocked when E2 already contains a voiced obstruent, as in (2) and (3). This blockage of rendaku is known as Lyman's Law after Lyman (1894) (although Lyman is probably not the first scholar who found this generalization: see Vance, 2022, for extended discussion on this point).

(1) Examples of rendaku
- a. /nise + **t**anuki/ → [nise + **d**anuki] 'fake raccoon'
- b. /juki + **k**uni/ → [juki + **g**uni] 'snow country'
- 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 by a local voiced obstruent
- a. /çito + **t**aba/ → [çito + **t**a**b**a], *[çito + **d**a**b**a] 'one bundle'
- b. /omo + **k**age/ → [omo + **k**a**g**e], *[omo + **g**a**g**e] 'resemblance'
- c. /moɾi + **s**oba/ → [moɾi + **s**o**b**a], *[moɾi + **z**o**b**a] 'cold soba'
- d. /çito + **h**ada/ → [çito + **h**a**d**a], *[çito + **b**a**d**a] 'people's skin'

[1] A constraint against two voiced obstruents within a morpheme also functions as a phonotactic restriction in native words in Japanese—no native morphemes seem to contain two voiced obstruents; e.g., [ɸuda] 'amulet' and [buta] 'pig' are both existing words, but *[buda] is not (Ito & Mester, 1986). Lyman's Law has been formalized as an OCP constraint on the feature [+voice] (Ito & Mester, 1986) or as a locally-conjoined constraint against a voiced obstruent within a morpheme (e.g., Alderete, 1997; Ito & Mester, 2003). The domain of these constraints was assumed to be a root/morpheme, not the adjacent syllables, implying the nonlocal nature of this constraint. See Kawahara & Zamma (2016) for a more thorough review of the theoretical treatments of Lyman's Law.

(3) Blocking of rendaku by Lyman's Law by a nonlocal voiced obstruent
   a. /ni + **t**amago/ → [ni + **t**ama**g**o], *[ni + **d**ama**g**o] 'boiled egg'
   b. /umi + **k**ɯrage/ → [umi + **k**ɯra**g**e], *[umi + **g**ɯra**g**e] 'sea jellyfish'
   c. /mitɕi + **ɕ**iɾube/ → [mitɕi + **ɕ**iɾu**b**e], *[mitɕi + **ʑ**iɾu**b**e] 'guide post'
   d. /oo + **h**aɕagi/ → [oo + **h**aɕa**g**i], *[oo + **b**aɕa**g**i] 'big excitement'

In existing words, the blockage of rendaku is almost exceptionless and it holds regardless of whether the blocker consonant is in the second syllable, as in (2) or in the third syllable, as in (3). Unambiguous cases of lexical exceptions of Lyman's Law include two local cases ([X-**z**a**b**ɯroo] 'Proper Name' and [hun-**ʑ**i**b**aru] 'to tightly bind') and one nonlocal case ([nawa-**b**aɕi**g**o] 'rope ladder').[2] Thus from the lexical patterns, it is not clear whether Lyman's Law is sensitive to a locality restriction or not. In other words, learners of Japanese, who are exposed to the Japanese data, would not know whether Lyman's Law would block rendaku to a stronger degree when the blocker and rendaku-undergoer are in the adjacent syllables, as expected from a cross-linguistic trend of dissimilation (Suzuki, 1998).[3]

Vance (1979) is a seminal experimental study on rendaku, which addressed this question using an experimental paradigm. He presented 50 nonce words, each combined with 8 real words, to 14 native speakers of Japanese and asked whether each compound should undergo rendaku or not. The results showed, first of all, that the blockage of rendaku by Lyman's Law is not deterministic, unlike in real words, and hence nonce words can undergo rendaku in such a way that they violate Lyman's Law. Moreover, the experiment found that for a number of speakers (eight out of fourteen), the blockage of rendaku is more likely when the blocker and the undergoer are in adjacent syllables than when they are separated by one intervening syllable.[4] This result would arguably instantiate a case of the emergence of the unmarked (TETU: McCarthy & Prince, 1994) in an experimental setting, since, as discussed above, there is very little, if any, lexical evidence for the locality effect on Lyman's Law (see e.g., Berent, 2013; Coetzee, 2009; Gallagher, 2013, 2016; Shinohara, 1997; Wilson, 2006; Zuraw, 2007, for other cases in which experiments have revealed a difference between two grammatical restrictions that are otherwise indistinguishable from the lexical evidence). One could also arguably take this result as a case

[2] There may be a few other possible cases of exceptions to Lyman's Law, although it is not clear that they are standard pronunciations: see §7.2.4 of Vance (2022) for detailed discussion on such forms.

[3] A locality effect on dissimilation is also expected to the extent that dissimilation has a phonetic underpinning, such as avoidance of perceptual confusion (Ohala, 1981; Stanton, 2019) and/or articulatory difficulty of repeating two similar/same gestures (Alderete & Frisch, 2007; Pulleyblank, 2002), because such phonetic problems are expected to be worse between local segments than between nonlocal segments.

[4] To be more specific, one speaker had no rendaku responses in either condition; four speakers had a very small-size reversal (e.g., 20% vs. 17%); and only one speaker had a fairly clear reversal (44% vs. 14%).

for the poverty of stimulus argument (Chomsky, 1986), because the lexical data from the actual spoken Japanese does not distinguish the local blockage effect and the nonlocal blockage effect.

However, a later experimental study by Kawahara (2012) failed to replicate this result by Vance (1979). This study was a naturalness judgment experiment, in which the participants were asked, using a 5-point Likert scale, how natural rendaku-undergoing forms were. That experiment had 36 test items (12 items for three conditions: no Lyman's Law violations, local Lyman's Law violations and nonlocal Lyman's Law violations). The data were collected from 54 native speakers of Japanese. In that experiment, forms with the local violation were judged to be slightly less natural than forms with the nonlocal violation (average naturalness ratings = 2.76 vs. 2.86), but this difference was not statistically significant, according to the test that Kawahara deployed.

Kawahara (2012) offered the following conjecture regarding where this difference between Vance (1979) and Kawahara (2012) might have come from. Another set of experiments reported by Ihara et al. (2009) showed that the locality effect of Lyman's Law decreased from 1984 when they ran their first experiment compared to 2005 when they ran their second experiment. It may have been the case that this trend continued and it disappeared completely by 2011, when Kawahara ran his experiment. In other words, the locality effect of Lyman's Law was fading away, as a part of historical change in Japanese phonology. Vance (2022), which reflects the most updated opinion by Vance himself, suspects that the fact that Vance (1979) found some evidence for a locality effect was due to some uncontrolled factors, implying that he now believes that Lyman's Law is not sensitive to a locality effect after all (see Vance, 2022: Section 7.2.2).

To settle these conflicting results from the previous studies, the experiments reported in the current paper revisit this question—is Lyman's Law sensitive to a locality effect after all? We were set out to run a new experiment with a large number of stimuli and a large number of participants, because one reason for why Kawahara (2012) failed to find the locality effect may have been due to a small *N*, i.e., the experiment simply lacked sufficient statistical power (see e.g., Chambers, 2017; Sprouse & Almeida, 2017; Vasishth & Gelman, 2021; Winter, 2019, for discussion on the general lack of statistical power in linguistics and neighboring fields).

One general issue that we had in mind as we revisited this old question, already addressed by these previous studies reviewed above, was "the replication crisis" (Chambers, 2017; Open Science Collaboration, 2015; Roettger, 2019; Sönning & Werner, 2021; Winter, 2019), in which many results that are published in previous research cannot be replicated by later studies. One reason behind this general problem is insufficient statistical power, resulting from an insufficient *N*, both in terms of participants and items. For the case at hand, Kawahara (2012) had only three items for each segment type that can undergo rendaku (/t/, /k/, /s/ and /h/, i.e., three items × four segments for each Lyman's Law violation condition). Another reason behind the

replication crisis may be the inappropriate use of (frequentist) statistical analyses (Chambers, 2017). In this respect too, Kawahara (2012) made a mistake of concluding a null effect given a statistically nonsignificant result using a frequentist analysis, when he says "the locality effect has disappeared by 2011" (p. 1197). One should not conclude a null effect given a nonsignificant result with a frequentist analysis.

To address these problems, our experiment included 72 stimuli and we collected data from about 200 speakers. We also resorted to a Bayesian analysis, as it would allow us to assess to what degree we can believe in a null effect (Gallistel, 2009), if the results were to show that no differences exist between a local violation of Lyman's Law and a nonlocal violation of Lyman's Law.

2. Experiment 1

2.1. Method

Following the open science initiative in linguistics as a step toward addressing the replication crisis problem (Cho, 2021; Winter, 2019), the raw data, the R markdown file and the Bayesian posterior samples are made available at an Open Science Framework (OSF) repository.[5]

2.1.1. Overall design

The current experiment consisted of three conditions: (1) nonce words whose rendaku would not result in any violations of Lyman's Law (e.g., [taɾuna]→[**d**aɾuna]), (2) nonce words whose rendaku would incur a local violation of Lyman's Law (e.g., [taguta]→[**d**a**g**uta]), and (3) nonce words whose rendaku would result in a nonlocal violation of Lyman's Law (e.g., [tatsu**g**a]→[**d**atsu**g**a]). The comparison between the first condition and the second condition would test the psychological reality of Lyman's Law, which has been confirmed by a number of previous experimental studies (Ihara et al., 2009; Kawahara, 2012; Kawahara & Sano, 2014a,b; Kawahara & Kumagai, 2023a,b; Vance, 1979). The comparison between the second condition and the third condition would test the (non)local nature of Lyman's Law, the main concern of the current experiment.

2.1.2. Stimuli

Table 1 shows the list of nonce word E2s used in Experiment 1. The experiment tested all four sounds that can undergo rendaku in contemporary Japanese (/t/, /k/, /s/ and /h/) with 6 nonce items in each cell. These resulted in a total of 72 stimuli (3 conditions × 4 consonant types × 6 items). The stimuli for the first two conditions were adapted from Kawahara & Kumagai (2023a).

[5] https://osf.io/ym79p/. We fully acknowledge that adopting the open science policy is not a panacea for the general replication crisis problem, but also note that it is nevertheless a necessary and useful first step that we can take toward addressing it.

None of the stimuli becomes a real word after rendaku. The syllable structure of the stimuli was controlled in that none of the stimuli contained a heavy syllable. Since the applicability of rendaku may be reduced when it results in identical CV mora sequences (Kawahara & Sano, 2014a,b), in no forms would rendaku result in CV moras that are identical to those in the second syllables or to those in third syllables. Since we chose to use [nise] 'fake' as E1 (see below), we avoided stimuli that begin with [se] as well.

	No violation		**Local violation**		**Nonlocal violation**	
/t/	[tamuma]	たむま	[taguta]	たぐた	[tatsuga]	たつが
	[tatsuka]	たつか	[tozumi]	とずみ	[tesago]	てさご
	[taɾuna]	たるな	[teguɾa]	てぐら	[tekibi]	てきび
	[tonime]	とにめ	[tazanu]	たざぬ	[takuga]	たくが
	[tekeha]	てけは	[tegesa]	てげさ	[tokoʑi]	とこじ
	[tokeho]	とけほ	[toboɸu]	とぼふ	[teçigi]	てひぎ
/k/	[kimane]	きまね	[kidaku]	きだく	[kitebe]	きてべ
	[kikake]	きかけ	[kobono]	こぼの	[kotɕiba]	こちば
	[kotona]	ことな	[kabomo]	かぼも	[kaɕido]	かしど
	[kumise]	くみせ	[kedeɾe]	けでれ	[kutɕibo]	くちぼ
	[konihe]	こにへ	[kuʑiha]	くじは	[kesodo]	けそど
	[kehaɾo]	けはろ	[kozana]	こざな	[katsuba]	かつば
/s/	[samaɾo]	さまろ	[sabaɾe]	さばれ	[sokabo]	そかぼ
	[sokato]	そかと	[sogeha]	そげは	[sohogi]	そほぎ
	[sutane]	すたね	[sobumo]	そぶも	[sukabi]	すかび
	[samohe]	さもへ	[sadanu]	さだぬ	[suhode]	すほで
	[soɾise]	そりせ	[sodoka]	そどか	[satage]	さたげ
	[sateme]	さてめ	[sudaɸu]	すだふ	[sokebi]	そけび
/h/	[honaɾa]	ほなら	[hobasa]	ほばさ	[hokida]	ほきだ
	[çinumi]	ひぬみ	[hazuke]	はずけ	[hekazu]	へかず
	[honiko]	ほにこ	[hogoɾe]	ほごれ	[hetado]	へたど
	[hakisa]	はきさ	[çigiɾo]	ひぎろ	[hategi]	はてぎ
	[heɾaho]	へらほ	[ɸuzumo]	ふずも	[çisuda]	ひすだ
	[çihonu]	ひほぬ	[hedeno]	へでの	[ɸuhode]	ふほで

Table 1: The list of nonce words used as E2s in Experiment 1. /h/ allophonically becomes [ç] before [i] and [ɸ] before [u].

2.1.3. Participants

The experiment was conducted online using SurveyMonkey (https://jp.surveymonkey.com). The participants were collected using a snowball sampling method, primarily on X (formerly Twitter), advertised on the first author's account. As a result, 162 speakers, who were native speakers of Japanese and had not heard about rendaku or Lyman's Law, voluntarily completed the online experiment. The numbers of speakers for each age group, provided by SurveyMonkey, were as follows: 29 (18–19 years old), 52 (20–29 years old), 38 (30–39 years old), 25 (40–49 years old), 14 (50–59 years old) and 4 (above 60 years old). In addition, the data from 39 additional participants, who earned an extra credit for completing the experiment, were collected from Keio University.[6] From this pool of data, however, we had to exclude the data from 17 students, because they were either a nonnative speaker of Japanese or were already familiar with rendaku.

Two speakers chose the no-rendaku response for all questions, whereas one speaker chose the yes-rendaku response for all questions; one participant chose only one yes-rendaku response. The data from these participants were also excluded, as it is likely that they were not paying serious attention to the task. As a result, the data from a total of 180 participants were considered in the following statistical analysis.

2.1.4. Procedure

In the instructions, the participants were told that when they combine two words to create a compound in Japanese, some combinations undergo voicing (i.e., rendaku); the example given was /kaki/ 'persimmon' becoming [gaki], when it is combined with [ɕibu] 'bitter'. It was explained to the participant that combining two words can result in a *dakuten* diacritic—which represents obstruent voicing in the Japanese orthography—at the beginning of the second element (e.g., か vs. が).

In the main session, the participants were presented with one stimulus item and were asked to combine it with [nise] 'fake' as E1 to make a compound. They were then asked whether the resulting compound would sound more natural with initial voicing (i.e., rendaku) or without initial voicing.

The stimuli were written in the hiragana orthography, which signals the presence of rendaku with a diacritic mark that generally represents obstruent voicing in the Japanese orthography. We used the hiragana orthography because rendaku applies primarily to native words, and hiragana is used to write native words in the Japanese orthographic convention. While the stimuli were presented in orthography, the participants were asked to read and pronounce each option before they answered each question. The stimuli in the main session were presented to the participants as obsolete native words that used to exist in Japanese, so that the participants would treat them

[6] We did not obtain the information about their age, but they were all most likely in their early twenties.

as native words (see Vance, 1979; Zuraw, 2000, for previous studies which used this method). A sample question is thus, "given an obsolete word [saɾita], when it is combined with [nise], which form sounds more natural, [nise-saɾita] or [nise-zaɾita]?".

Each participant was assigned a uniquely randomized order of stimuli, using the randomization function of SurveyMonkey. Prior to the main session, the participants went through a practice question with the [nise-saɾita] versus [nise-zaɾita] example so that they could familiarize themselves with the task. Since there are no right/wrong answers, no feedback was given.

2.1.5. Statistical analysis

For statistical analysis, we fit a Bayesian mixed effects logistic regression model, using the brms package (Burkner, 2017) and R (R Development Core Team, 1993–) (for accessible introductions to Bayesian modeling, see e.g., Franke & Roettger, 2019; Kruschke, 2014; Kruschke & Liddell, 2018; McElreath, 2020; Vasishth et al., 2018). Bayesian analysis takes both a prior distribution (if any) and the obtained data into consideration and produces a range of possible values (= posterior distributions) for each parameter that we would like to estimate. One advantage of Bayesian analysis is that we can interpret these posterior distributions as directly reflecting the likely values of these estimates, unlike the 95% confidence intervals that we obtain in a frequentist analysis. Another advantage is that it would allow us to examine with how much confidence we can believe in a null effect (Gallistel, 2009). Since Kawahara (2012) obtained a "statistically nonsignificant result", this was an important advantage of using Bayesian analysis for the current experiment.

One heuristic to interpret the results of Bayesian regression models is to examine the middle 95% of the posterior distribution, known as *95% Credible Interval* (henceforth, *95% CrI*), of an estimated parameter. If that interval does not include 0, we can interpret that effect to be meaningful/credible. However, with Bayesian analysis, we do not need to commit ourselves to a "meaningful" versus "nonmeaningful" dichotomy, as in a frequentist "significant" vs. "nonsignificant" dichotomy. To be more concrete, another way to interpret the results of Bayesian regression models is to calculate how many posterior samples of a particular coefficient are in an expected direction. In what follows we present both ways of interpretation.

The details of the model specifications in the current model were as follows. The dependent variable was whether each item was judged to undergo rendaku or not (rendaku-undergoing response = 1 and non-rendaku-undergoing response = 0). For independent variables, one main fixed factor was three conditions regarding Lyman's Law (no violation vs. local violation vs. nonlocal violation). The reference level of this factor was set to be the local violation condition, so that we can compare (i) the difference between no violation and local violation (i.e., the psychological reality of Lyman's Law) and (ii) the local violation and the nonlocal violation (i.e.,

the locality of Lyman's Law). Another fixed factor was sound type (i.e., /t/-/k/-/s/-/h/). For this factor, the baseline was arbitrarily set to /h/, because we had no particular a priori reason to choose one segment over the others. The interaction term between the two factors was also coded, because we wanted to see whether the effects of Lyman's Law, if any, would generalize to all four segments. The model also included a random intercept of items and participants in addition to random slopes of participants for both of the fixed factors and their interaction term.

For prior specifications, we used 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). We ran four chains with 4,000 iterations and disregarded the first 1,000 iterations as warmups, as running only 2,000 iterations resulted in inappropriate effective sample size (ESS) values. As a result, all the $\hat{R}$ values for the fixed effects were 1.00 and no divergent transitions were detected, i.e., the four chains mixed successfully. Complete details of this analysis are available in the R markdown file available at the OSF repository mentioned above.

2.2. Results

2.2.1. General results

Figure 1 shows the rendaku application rate for each condition in the form of violin plots, in which their widths represent normalized probability distributions. Each facet shows a different segment type. Within each facet, each violin shows the three critical conditions. Transparent circles, jittered slightly to avoid overlap, represent averaged responses from each participant within each violin. Solid red diamonds are the averages in each condition. Abstracting away from the differences among the four segments, the three conditions resulted in the following rendaku application: (1) no Lyman's Law violation = 60.8% (2) local Lyman's Law violation = 32.4% (3) nonlocal Lyman's Law violation = 41.6%.[7] The markdown file available at the OSF repository provides segment-specific average values.

[7] One may wonder why we did not obtain (near-)100% rendaku application responses for the no Lyman's Law violation condition. This result is actually expected, as the application of rendaku is affected by various factors (e.g., Kawahara, 2015a; Rosen, 2003, 2016; Vance, 2014, 2016, 2022). For instance, rendaku is limited to apply mainly to native words and some Sino-Japanese words, but it does not apply to recent loanwords or mimetic words (Vance, 2022). Moreover, for some lexical items, the application of rendaku is optional; e.g., both [sori + ɕita] and [sori + ʑita] 'retroflex' are possible forms. Finally, lexical items like [kasu] 'dregs' and [tsuju] 'dew' never undergo rendaku, despite the fact that there are no linguistic factors that would prevent them from undergoing rendaku.

Having said that, however, we also have some reasons to consider rendaku to be a (semiproductive) grammatical process (Kawahara, 2015a). Rendaku, for instance, is blocked by a phonological restriction such as OCP(labial), a constraint that prohibits two labial constraints in the adjacent syllables; i.e., forms that begin with /h…m/ barely undergo rendaku, since it would result in two adjacent labial consonants ([b…m]) (Kawahara et al., 2006). Rendaku, as shown in this and many previous experiments, also interacts with OCP(+ voice). These observations suggest that rendaku interacts with cross-linguistically motivated phonological constraints, which implies that rendaku too is at least in part phonological in nature.

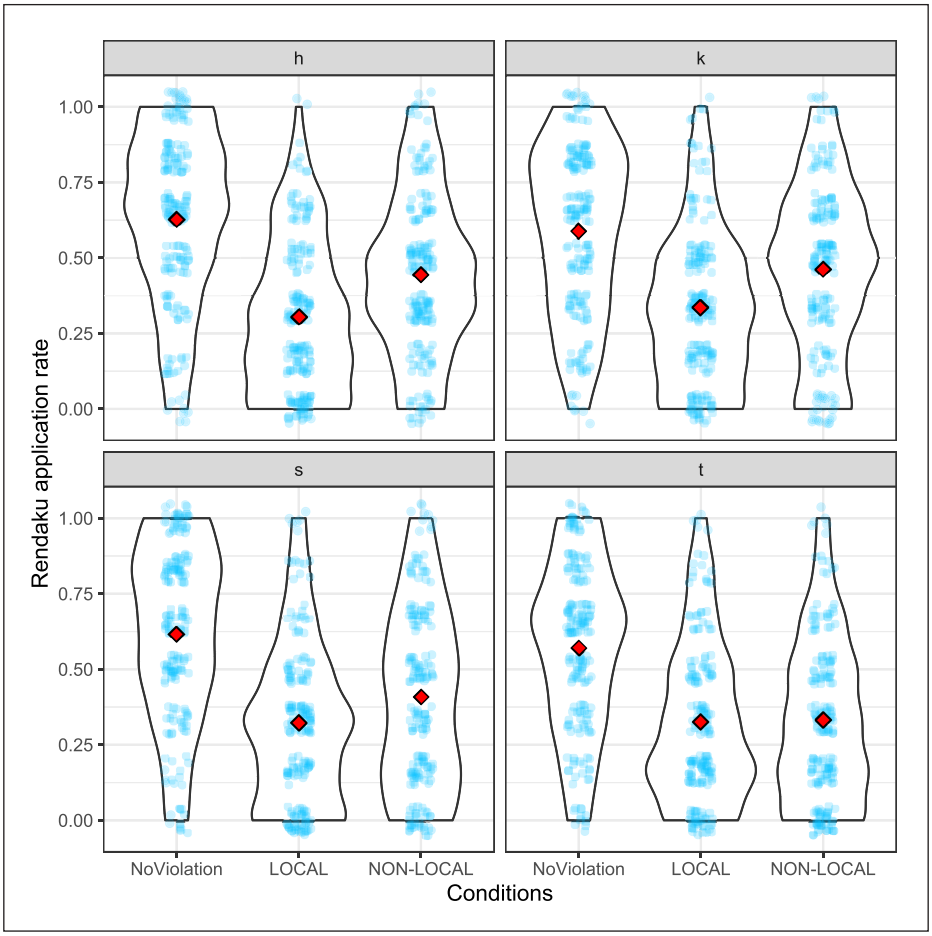

Figure 1: Comparison between the three critical conditions, with each facet showing a different segment type. Transparent circles, which represent averaged responses from each participant, are jittered slightly to avoid overlap. The red diamonds show the averages within each violin.

We observe that the first condition (no violations of Lyman's Law) showed higher rendaku responses compared to the second condition (the local violation of Lyman's Law), providing support for the psychological reality of Lyman's Law, which was shown by a number of previous studies (Ihara et al., 2009; Kawahara, 2012; Kawahara & Sano, 2014a,b; Kawahara & Kumagai, 2023a,b; Vance, 1979).

More interestingly, the second condition (the local violation of Lyman's Law) generally showed lower rendaku responses than the third condition (the nonlocal violation of Lyman's Law), although this difference is very small in the /t/ facet. Overall, then, the current results appear to support that of Vance (1979), not that of Kawahara (2012)—Lyman's Law does seem to exhibit a locality effect in nonce words, at least for /h/, /k/ and /s/.

The model summary of the Bayesian mixed effects logistic regression analysis is provided in **Table 2**. The intercept is negative, as it represents the baseline condition (/h/, local violation), whose average response is lower than 50%. As for the sound type (=the coefficients in (b)), for which /h/ serves as the baseline, all of the relevant 95% CrIs for the

coefficients include 0, suggesting that differences among the four segment types were not very meaningful. The interaction terms in (d)—interactions between the segment type and the difference between the no-violation and the local violation—were also not very credible, suggesting that the local version of Lyman's Law functions to a comparable degree across the four segments, although for /k/ and /t/, they are leaning toward the negative, i.e., the effects of local Lyman's Law tend to be smaller. The main effect of the difference between the no-violation and the local violation ((c), top) was very credible, supporting the psychological reality of Lyman's Law.

Variable	Specific comparison	β	error	95% CrI
(a) intercept	(/h/, local)	−0.97	0.17	[−1.31, −0.62]
(b) sound type	/k/	0.13	0.23	[−0.31, 0.57]
	/s/	0.04	0.23	[−0.40, 0.48]
	/t/	0.08	0.23	[−0.38, 0.52]
(c) condition	no-violation vs. local	1.64	0.24	[1.18, 2.11]
	local vs. nonlocal	0.69	0.23	[0.24, 1.15]
(d) interactions I	/k/:no-violation vs. local	−0.34	0.32	[−0.96, 0.29]
	/s/:no-violation vs. local	−0.07	0.31	[−0.69, 0.54]
	/t/:no-violation vs. local	−0.38	0.32	[−1.00, 0.24]
(e) interactions II	/k/:local vs. nonlocal	−0.04	0.31	[−0.65, 0.57]
	/s/:local vs. nonlocal	−0.24	0.32	[−0.87, 0.38]
	/t/:local vs. nonlocal	−0.69	0.32	[−1.31, −0.07]

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

Most interestingly for the case at hand, the main effect of the difference between the local violation and nonlocal violation ((c), bottom) was also credible, at least at the baseline level /h/. However, the interaction term between the locality effect and /t/ was also credible, suggesting that we should look at the locality effect of Lyman's Law for each segment. We thus calculated how many samples of the locality effect were in the expected direction in the posterior distributions—$p(\beta > 0)$—for each segment type, which represent how likely the nonlocal Lyman's Law condition induced higher rendaku responses than the local Lyman's Law condition.

The results show that $p(\beta > 0)$ is .503 for /t/, .996 for /k/, .970 for /s/ and .998 for /h/. We thus conclude that Lyman's Law is sensitive to a locality effect for all segments but /t/. Statistically speaking, in short, the current results appear to accord better with Vance (1979), than with Kawahara (2012), for /k/, /s/ and /h/.

For the sake of completeness, we also calculated $p(\beta > 0)$ for the difference between the no-violation condition and the local violation condition. The results show that it is 1 for all segments—i.e., the effects of Lyman's Law are undoubtedly present for all segment types.

2.2.2. By-speaker analysis

One question that arises regarding the current results, given the variability observed in **Figure 1**—and also given that Kawahara (2012) failed to find such an effect—is about interspeaker differences.[8] Among the speakers who participated in the current experiment, how generally does the locality effect hold? With this question in mind, **Figure 2** plots, for each participant, the average rendaku application rate for the local violation condition and the nonlocal violation condition. The dots above the diagonal axis correspond to speakers who are sensitive to a locality effect in the expected direction, and there were many of them. However, there were a number of participants around the diagonal axis, who are not sensitive to the locality effect. And rather surprisingly, there were also some below the diagonal axis, who represent an "anti-locality" effect. Nevertheless, there were many more speakers who showed an expected locality effect than those who showed an anti-locality effect (113 vs. 51; 16 had an equal number of yes-rendaku responses between the two conditions).

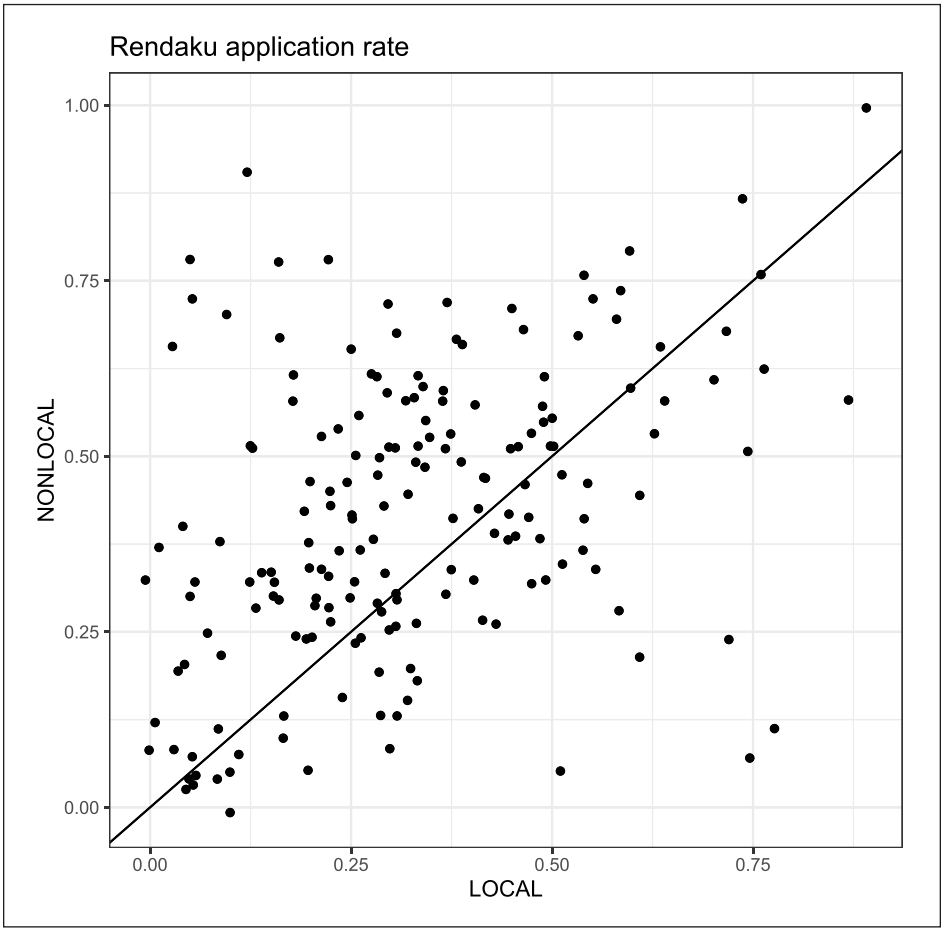

Figure 2: Comparison between the local violation condition and the nonlocal violation condition by each speaker (Experiment 1).

[8] Our experiment is not the first one to have found such interspeaker variability. In fact, finding interspeaker differences is the norm, rather than an anomaly, in rendaku-related experiments (Kawahara, 2012; Kawahara & Sano, 2014a; Kawahara & Kumagai, 2023a,b; Vance, 1979, 1980).

Given that Vance (1979) found that eight out of the fourteen speakers showed the locality effect in the expected direction, and that one speaker showed a clear reversal (44% vs. 14%), the current results may be comparable to that of Vance and thus may not be too surprising. In this sense too, we replicated the results by Vance with a much larger number of participants.

2.3. Discussion: Experiment 1

The first and foremost important finding of the current study is to have shown that Lyman's Law is, at least for many speakers, indeed sensitive to a locality effect, *a la* Vance (1979), for the three segments other than /t/. This is an interesting result especially because, as discussed in the introduction, evidence from the Japanese lexicon does not distinguish the local violation from the nonlocal violation.

The current finding thus may instantiate a case of the emergence of the unmarked (TETU: McCarthy & Prince, 1994) in an experimental setting. More broadly speaking, the current result shows that there may be an aspect of phonological knowledge of Japanese that cannot be learned from the lexical patterns of rendaku and Lyman's Law alone (see Berent, 2013; Coetzee, 2009; Gallagher, 2013, 2016; Shinohara, 1997; Wilson, 2006; Zuraw, 2007, for similar results, in which the difference between two grammatical conditions emerges only in experimental settings). This result supports the role of abstract grammatical knowledge which somehow imposes a locality effect on Lyman's Law, although we admit that it is puzzling that some speakers exhibit such an "anti-grammatical effect."[9]

We note, however, the preceding argument rests on the assumption that learners use only rendaku-related evidence to learn the grammatical status of Lyman's Law. It may be possible, however, that the local nature of Lyman's Law can be learned from somewhere else; for instance, there may be more loanwords which incur a local violation of Lyman's Law (e.g., [**b**a**g**u] 'bug') than those that incur a nonlocal violation of Lyman's Law (e.g., [**d**aijamon**d**o] 'diamond'). An anonymous reviewer also pointed out that even among the existing native words, there may not be a lot of words that support the nonlocal effect of Lyman's Law. In addition to the examples we provided in (3), there are [hitsuʑi] 'sheep', [kuɾage] 'jelly fish' and [kotoba] 'words', none of which undergo rendaku, but there may not be many others. To the extent that phonotactic restrictions that are supported by more lexical items are more robustly represented in speakers' grammars, the current results may be attributed to this lexical tendency. While we are open to these alternative possibilities, the importance of the current findings remains robust, we believe, whatever the source of the locality effect is.

[9] Here is an admittedly post hoc explanation of how such antilocality pattern may have arisen in the current experiment. An anonymous reviewer pointed out that in the local condition, when the stimuli undergo rendaku, the first two syllables can resemble the beginning of existing (Sino-Japanese) compounds; for example, the nonce stimulus [tatsuga], when it becomes [datsuga], may have sounded similar to existing compounds like [datsugoku] 'prison break', [datsu-bou] 'hats off', [datsu-zoku] 'unworldness', etc. On the other hand, rendaku in the local condition does not result in resemblance with existing native or Sino-Japanese words, as there are no words containing two voiced obstruents in adjacent syllables. Thus, those participants who showed an anti-locality effect may have chosen options that sound similar to existing Sino-Japanese compounds. While we find this possibility interesting, examining this post hoc speculation in full detail needs to be executed in a separate study.

Some more questions arise from the current results, not all of which we can answer in this paper. First, we have no good explanation regarding why /t/ behaves differently from /k/, /s/ and /h/. As far as we know, there is nothing that is special about /t/—or [d]—in Japanese, rendaku-related or otherwise, that would make it exceptional to the locality effect of Lyman's Law. Recall that there is very little evidence for the local nature of Lyman's Law in the Japanese lexicon after all. Second, we are unable to offer a good explanation for why there is a nontrivial degree of interspeaker variability, as in **Figure 2**; neither are we able to offer a solid explanation regarding why there are speakers who show the "anti-locality" effect (though see footnote 9 for a post-hoc speculative hypothesis).

Finally, a new question arises regarding why Kawahara (2012) failed to find a difference between the local condition and the nonlocal condition. We find the last question to be the most important one to address, partly because it led Vance to consider his old results an artifact of uncontrolled factors (Vance, 2022: Section 7.2.2.). Therefore, in the next experiment we attempted to address this last question.

3. Experiment 2

We can consider two possibilities regarding why Kawahara (2012) failed to find a locality effect: (1) a naturalness judgment experiment, for some reason or another, was not a good task to reveal that effect or (2) the experiment by Kawahara lacked sufficient statistical power, i.e., *N* was too small. Recall that there were only three items for each segment-condition combination. While 54 participants may not be a very small number of speakers for a linguistic experiment, it may nevertheless have been insufficient. To tease apart these two possibilities, we attempted to replicate Kawahara (2012) with a larger number of speakers.

3.1. Methods

Since we used up a pool of participants who can take a rendaku-related experiment (recall that we needed participants who are not familiar with either rendaku or Lyman's Law), we resorted to the Buy Response function offered by SurveyMonkey, which is limited to a maximum of 50 questions. Therefore, we limited ourselves to two segments, /k/ and /s/, one plosive and one fricative, both of which showed a clear locality effect in Experiment 1.

The methodological details of Experiment 2 were similar to those of Experiment 1, except for a few differences. First, Experiment 2 was a naturalness judgment experiment, in which the participants were asked to rate the naturalness of rendaku-undergoing forms using a 5-point Likert scale, where 5 was labeled as 'very natural' (とても自然だ) and 1 was labeled was 'very unnatural' (とても不自然だ) (the other points on the scale were not labeled). For statistical analysis, we used a Bayesian *ordinal* logistic regression with the same random factor structure as Experiment 1. The baseline for the segmental difference was arbitrarily chosen as /k/. Again the R markdown file available at the OSF repository shows complete details of the analysis.

A total of 187 native speakers of Japanese participated in this study. Among those, 15 speakers used the same rating for all responses, indicating that they were not paying serious attention to the task. Their data were excluded from further analysis. This left us with the following numbers of speakers in each age group: 3 (18–19 years old), 20 (20–29 years old), 27 (30–39 years old), 37 (40–49 years old), 60 (50–59 years old) and 25 (above 65 years old).

3.2. Results: Experiment 2

Figure 3 shows the distribution of naturalness ratings for the three conditions, with the two facets showing the two segment types. We observe that the first condition with no violations of Lyman's Law was generally rated as most natural. The forms with a local violation of Lyman's Law were rated as least natural and those with the nonlocal violation were rated as intermediate. The grand averages in each of the three conditions were as follows: no Lyman's Law violation = 3.09, local Lyman's Law violation = 2.73 and nonlocal Lyman's Law violation = 2.86.

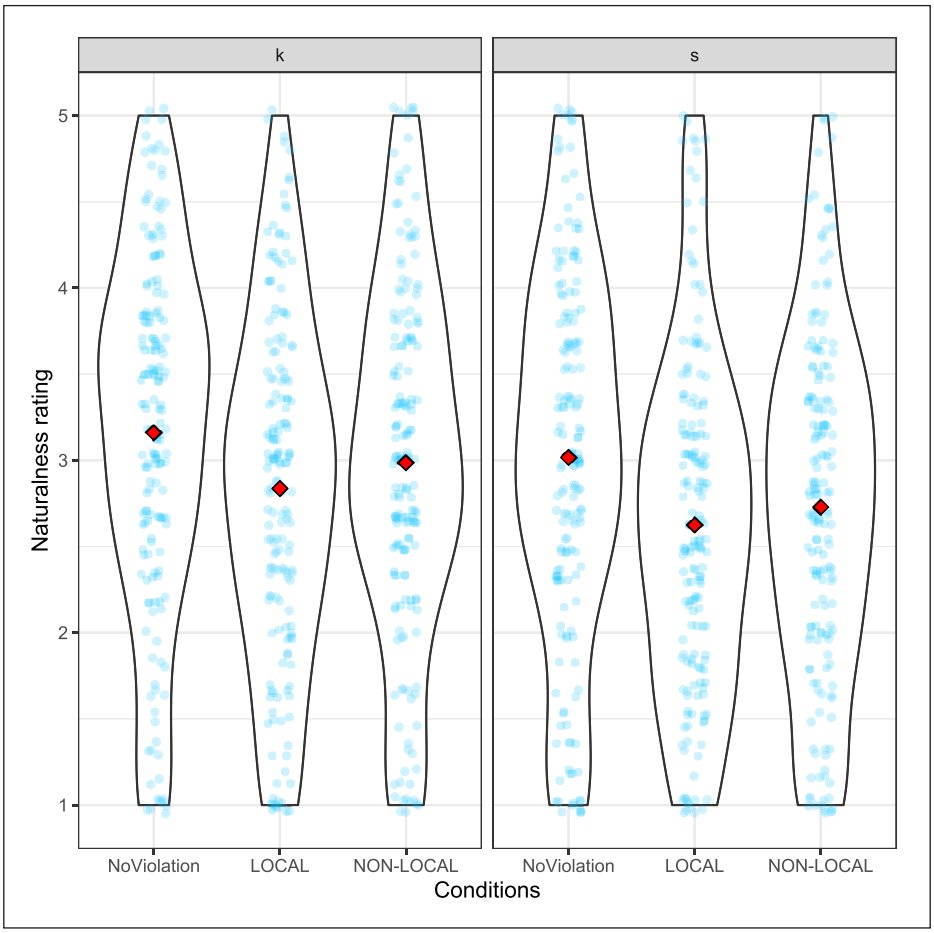

Figure 3: Comparison between the three critical conditions in naturalness ratings (Experiment 2).

The model summary of the results in Experiment 2 appears in **Table 3**. The 95% CrI for the segmental difference (coefficient in (b)) does not include zero, and is highly skewed toward negative values, suggesting that [z]-initial forms were rated less natural than [g]-initial items. The 95% CrI for the difference between the no-violation and the local violation (coefficient (c), top) does not include 0, suggesting the robustness of the effects of (local) Lyman's Law. In terms of the posterior probabilities of the coefficients being positive, the effects of Lyman's Law were clear for both segments: for /k/, $p(\beta > 0) = .998$ and for /s/ as well, $p(\beta > 0) = .999$. These results are compatible with the results of Kawahara (2012).

Variable	Specific comparison	β	error	95% CrI
(a) (baseline = /k/, local)				
intercept[1]		−2.54	0.24	[−3.01, −2.07]
intercept[2]		−0.58	0.24	[−1.04, −0.12]
intercept[3]		1.31	0.24	[0.84, 1.77]
intercept[4]		3.49	0.24	[3.02, 3.96]
(b) segment		−0.48	0.24	[−0.96, −0.01]
(c) condition	no-violation vs. local	0.81	0.26	[0.30, 1.32]
	local vs. nonlocal	0.36	0.25	[−0.12, 0.84]
(d) interactions	seg:no-violation vs. local	0.13	0.34	[−0.54, 0.80]
	seg:local vs. nonlocal	−0.13	0.34	[−0.81, 0.54]

Table 3: Summary of the Bayesian mixed effects ordinal logistic regression model (Experiment 2).

The 95% CrI for the difference between the local and nonlocal violation conditions (coefficient (c), bottom) includes 0, but it is skewed toward positive values, suggesting that the nonlocal violation condition tended to induce more natural responses than the local violation condition. In terms of the probabilities of the β-coefficients being in the expected direction in the posterior distributions, the probability of the local violation being less natural than the nonlocal violation at the baseline level (=/k/) was $p(\beta > 0) = .926$. The locality comparison at the level of /s/ was $p(\beta > 0) = .820$. Thus, we are at least 82% positive that the local and nonlocal violation conditions induced different naturalness ratings. These results are not as robust as those found in Experiment 1, but we find the converging results between the two experiments to be encouraging.

Figure 4 shows the by-speaker analysis of the results in Experiment 2. Those dots above the diagonal axis represent speakers who show a locality effect, whereas those who are below the

diagonal line are speakers who show an antilocality effect. As with Experiment 1, we do observe that both types of speakers exist, but more speakers show a locality effect than an antilocality effect, hence the overall results in **Figure 3** (93 vs. 57 speakers; 22 speakers showed the same average rating between the two conditions).

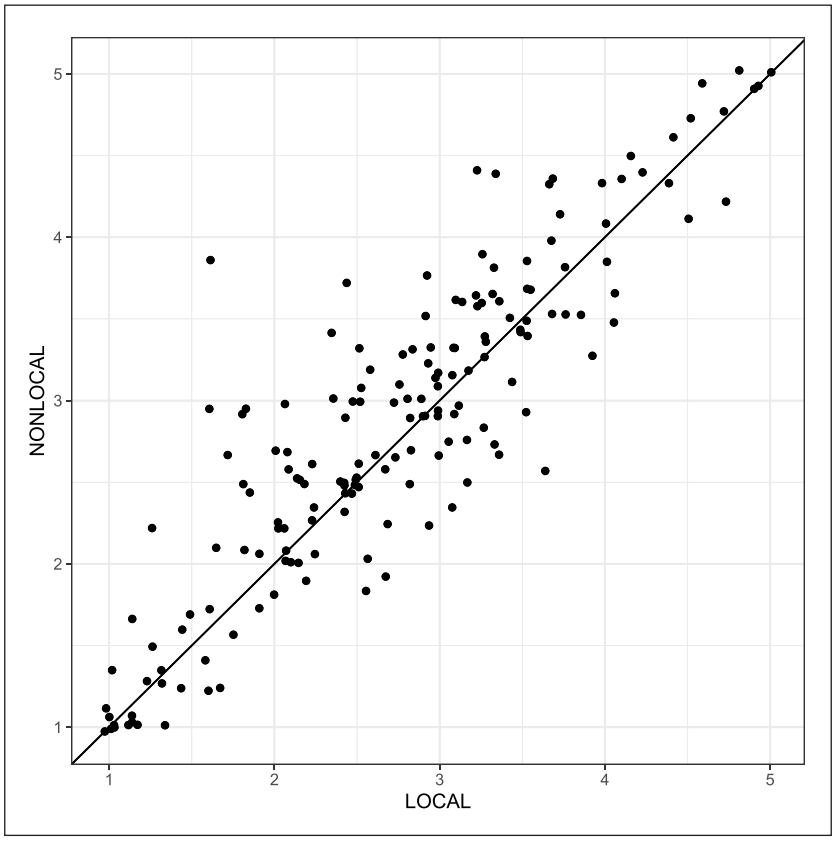

Figure 4: Comparison between the local violation condition and the nonlocal violation condition by each speaker (Experiment 2).

3.3. Discussion: Experiment 2

We thus observe at least modest evidence (i.e., 82%–93% confidence) that the local violation of Lyman's Law and the nonlocal violation induce different naturalness ratings—i.e., local violation tend to be judged to be less natural, contrary to the conclusion drawn by Kawahara (2012). We note, however, that Kawahara did observe a trend in the expected direction and that the sizes of differences were not radically different between Kawahara (2012) and the current experiment (2.76 vs. 2.86 = 0.10 in Kawahara, 2012, and 2.73 vs. 2.86 = 0.13 in the current experiment). We also note that if we were using a frequentist analysis and were stuck with a *p*

$<$ .05 threshold, then the current results may have turned out to be "nonsignificant." The use of Bayesian analysis allowed us to see how confident we can be about the difference between the local condition and the nonlocal condition, without being bound to the "significant vs. nonsignificant" dichotomy.

Having said that, it is also true that the results are less clear cut in Experiment 2 than in Experiment 1, which suggests that naturalness rating experiments using a Likert scale may not be an optimal method to reveal the locality effect of Lyman's Law. One reason may be that the participants were presented only with one form (i.e., rendaku-undergoing form), whereas in Experiment 1, the participants were asked to compare rendaku-undergoing forms and non-rendaku-undergoing forms (see Daland et al., 2011; Kawahara, 2015b; Sprouse & Almeida, 2017, for related observations, especially in terms of how these two experimental paradigms can differ). Another reason may be that some participants may have had difficulty in interpreting what "naturalness" really means, especially when they are given nonce words.

While we fully acknowledge that it is not desirable to rerun a statistical test after the results are known and interpreted (Kerr, 1998), having seen the results of Experiment 2 prompted us to see what would happen if we ran a Bayesian analysis on the data obtained by Kawahara (2012). Explicitly bearing in mind that this is a post-hoc reanalysis, whose results should be interpreted with much caution, we ran a Bayesian analysis that is similar to the one that was used for our Experiment 2. However, since there were only three items for each segment-condition combination, we dropped the segmental difference as a fixed factor from the model, as a three-level random factor is inappropriate (Snijders & Bosker, 2011). There is an R markdown file available in the OSF repository which shows the complete details of this reanalysis.

The result of the reanalysis shows that for the difference between the local violation condition and the local violation condition, $p(\beta > 0) = .94$ even for this old dataset. While this model is incomplete in that we had to drop segment type as a factor, the data obtained by Kawahara (2012) seem to be comparable with what we obtained in Experiment 2. We reiterate, however, that this is a completely post-hoc conclusion.

Finally, we would like to come back to the possibility that we raised in the introduction; namely, the locality effect was decreasing over time as a part of an on-going sound change in Japanese (Ihara et al., 2009; Kawahara, 2012). To address this hypothesis, **Figure 5** plots the differences in rating between the local condition and the local condition in the current experiment—standing for the degrees of the locality effect—on the *y* axis, against the age group categories provided by SurveyMonkey, in which higher values represent older speakers. If the hypothesis were true, older speakers should show larger differences. As we can observe in the figure, however, there is no substantial correlation between the two measures.

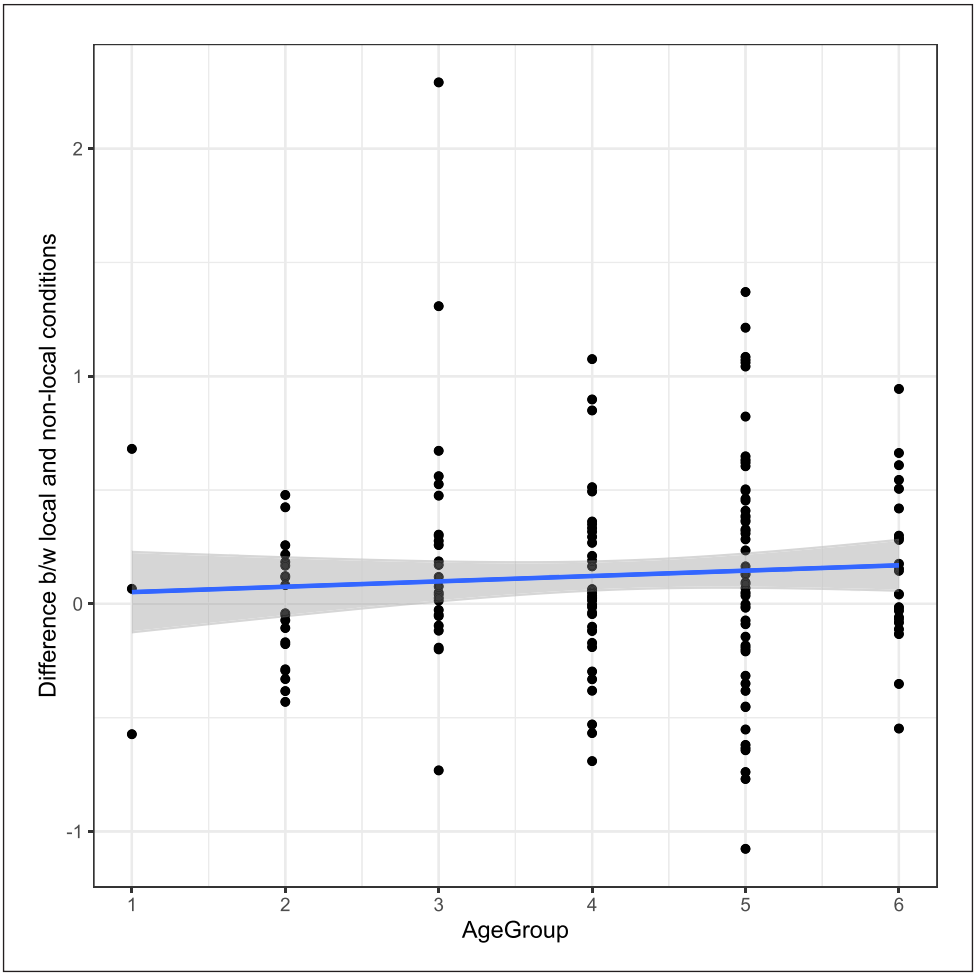

Figure 5: The degree of the locality effect (the differences in rating between the local violation condition and the local violation condition) plotted against the age groups.

4. Overall discussion

The most important finding of the current experiments, we believe, is empirical: we found that generally speaking, Lyman's Law shows a locality effect in that its dissimilatory force is stronger when the two voiced obstruents are in adjacent syllables than when they are not, as Vance (1979) showed. This may not be too surprising given that dissimilatory forces tend to function in this manner cross-linguistically (Suzuki, 1998). The result, on the other hand, can be taken to be indeed surprising, because the Japanese lexicon does not offer clear evidence for this locality effect of Lyman's Law. Recall that Vance (2022) himself, who found the effect in 1979, later speculated that his finding was due to some uncontrolled factors.

The current results also offer some lessons for experimental phonology in general. First, the fact that Kawahara (2012) failed to find a "statistically significant" difference suggests that using

a frequentist analysis as in Kawahara (2012) may not have been an optimal strategy to identify a linguistic effect (see Chambers, 2017; Vasishth & Gelman, 2021, for related discussion). Second, a naturalness judgment experiment may be a less reliable tool compared to a forced judgment task—it may be easier for naive participants to choose between two distinct forms than making naturalness judgments of one form in isolation (see Daland et al., 2011; Kawahara, 2015b; Sprouse & Almeida, 2017). These lessons open up an opportunity for future research: to reexamine the aspects of rendaku that have been studied in previous experimental studies (Kawahara, 2016), with a large number of speakers and items, ideally using a Bayesian method.

Finally, we would like to close this paper by acknowledging some limitations of the current experiments. First, we used the hiragana orthography to present the stimuli. While this is not an uncommon practice in the previous experimental studies on rendaku—largely because the presence of rendaku is clearly signaled in the orthography—and we asked the participants to read and produce the stimuli before giving their responses, it would be interesting and important to replicate the current experiments with auditory stimuli (see Vance et al., 2023, for a recent experimental study on rendaku which used auditory stimuli). Also, in addition to deploying a forced-choice format, it would also be informative to examine what would happen if we ask the participants to produce novel compounds themselves. We would like to leave these ideas for followup studies.

Data accessibility statement

The data, code and other materials are available at https://osf.io/ym79p/.

Ethics and consent

The current experiments were conducted with approval from the first author's institute.

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

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Competing interests

The authors have no competing interests to declare.

Author contributions

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

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