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The non-local nature of Lyman's Law revisited*

Shigeto Kawahara and Gakuji Kumagai
Keio University and Kansai University

Abstract

Rendaku is a morphophonological alternation in Japanese in which the first obstruent of a second member of a compound becomes voiced (e.g. /nise+**t**anuki/ → [nise-**d**anuki]). Lyman's Law blocks this voicing process when the second member already contains a voiced obstruent, whether the blocker consonant is in the second syllable (e.g. /zaru+soba/ → [zaru-**s**o**b**a]) or in the third syllable (e.g. /çi+tokage/ → [çi+**t**oka**g**e]). Vance (1979), a seminal experimental study on rendaku, showed that in nonce words, the blockage of rendaku by Lyman's Law is not deterministic; moreover, it found some evidence that the blockage effect tends to be stronger when the blocker consonant is in the second syllable than in the third syllable, i.e. Lyman's Law may be sensitive to a locality effect in nonce words. On the other hand, a naturalness judgment experiment by Kawahara (2012) failed to find this locality effect. To settle these conflicting results from the past studies, with a general issue of the replication crisis in linguistics in mind (Sönning & Werner 2021), we first conducted a large scale forced-choice experiment with 72 stimuli. The analysis of the responses from 180 native speakers of Japanese shows that Lyman's Law is, at least for many speakers, sensitive to a locality effect. To investigate why Kawahara (2012) failed to find a locality effect, we next replicated Kawahara (2012) with a larger number of speakers (187 participants), which found some evidence that the locality effect is identifiable in a naturalness judgment experiment as well. We conclude that Lyman's Law is indeed sensitive to a locality effect, at least for many speakers of the contemporary Japanese, supporting the original insight by Vance (1979).

Keywords: rendaku, Lyman's Law, dissimilation, locality, replication, experimental phonology
Approximate word count: 6,000

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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 and 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 famous case of similarity-based phonotactic restrictions in Arabic is also more stringent between two adjacent consonants than between two non-adjacent 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 non-local 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**a**b**a/ → [çito+**t**a**b**a], *[çito+**d**a**b**a] 'one bundle'
b. /omo+**k**a**g**e/ → [omo+**k**a**g**e], *[omo+**g**a**g**e] 'resemblance'
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], *[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 (Alderete 1997; Ito & Mester 2003). The domain of these constraints was assumed to be a root/morpheme, not the adjacent syllables, implying the non-local 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 non-local voiced obstruent

a. /ni+**t**ama**g**o/ → [ni+**t**ama**g**o], *[ni+**d**ama**g**o] 'boiled egg'

b. /umi+**k**uɾa**g**e/ → [umi+**k**uɾa**g**e], *[umi+**g**uɾa**g**e] 'sea jellyfish'

c. /mitɕi+ɕiɾu**b**e/ → [mitɕi+ɕiɾu**b**e], *[mitɕi+ʑiɾu**b**e] 'guide post'

d. /oo+**h**aɕa**g**i/ → [oo+**h**aɕa**g**i], *[oo+**b**aɕa**g**i] 'big excitement'

In existing words, the blockage of rendaku is almost exception-less 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-**za**b**u**ɾoo] 'PROPER NAME' and [hun-ʑi**b**aɾu] 'to tightly bind') and one non-local 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 fourteen 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 the 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, Shinohara 1997, Gallagher 2013, 2016, Wilson 2006 and 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 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 non-local blockage effect.

[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 non-local segments.

[4] To be more specific, one speaker had no rendaku responses in either conditions; 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%).

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 non-local 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 non-local violation (average naturalness ratings = 2.76 vs. 2.86), but this difference was not statistically significant, according to the test that Kawahara (2012) 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 has disappeared completely by 2011, when Kawahara run 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 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.

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 number of N, i.e., the experiment simply lacked a 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 number of 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 $\times$ 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 non-significant 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 non-significant 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 access 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 non-local violation of Lyman's Law.

Before proceeding to the report of the experiment, we would like to illustrate some natures of rendaku in further detail, which become relevant as we interpret the experimental results. First, the application of rendaku is not as straightforward as the examples in (1)-(3) may appear to suggest, since both various linguistic and lexical factors affect its applicability (e.g. Kawahara 2015a; Rosen 2003, 2016; Vance 2014, 2016, 2022). Rendaku is first of all limited to apply mainly to native words and some Sino-Japanese words, and it does not apply to recent loanwords or mimetic words (Vance 2022). The story is more complicated, however; for instance, for some lexical items, both forms—with or without rendaku—are possible; e.g. both [soɾi+ɕita] and [soɾi+ʑita] 'retroflex' are possible forms. Moreover, we observe some non-negligible degrees of inter-speaker variability with regards to the application of rendaku as well (see especially Vance 2022: §7.7 on this topic). 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 (these items are called "rendaku-immune": Rosen 2003). In short, it is not the case that rendaku applies to all lexical items, even when all the linguistic conditions are met. This is probably why Vance (2022) calls rendaku "irregular phonological marking" in the title of his recent book.

With this said, however, we would like to also make it clear at this point that we have some compelling reasons to consider the phenomenon to be a (semi-)productive (morpho-)phonological process as well (see Kawahara 2015a for an extended review of the arguments in favor of this view, though see also Ohno (2000) for a lexicalist view of rendaku). 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 noted above, also interacts with with OCP(+voice) (i.e. Lyman's Law). 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. In addition, Kobayashi et al. (2014) present evidence based on ERP patterns that rendaku is a ruled-governed process.

Another important aspect of Rendaku, as revealed by the previous experimental studies on this phenomenon, is that when native speakers of Japanese judge the applicability of rendaku, the results show that rendaku is only semi-productive but that there is a rather large between-speaker variability (Kawahara 2012; Kawahara & Sano 2014a; Kawahara & Kumagai 2023a,b; Vance 1979, 1980). Even given 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 reviewed above. Nonce words that do not violate Lyman's Law usually undergo rendaku about 50%–60% of the time on average (Kawahara & Sano 2014a; Kawahara & Kumagai 2023a,b). In addition, we almost always observe inter-speaker variability with regards to how often rendaku is applied to nonce words, but the source of such inter-speaker variability is yet to be revealed.

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 evident in nonce word experimentation, suggesting that rendaku shows systematicity. To sum up, although rendaku shows some irregularity, previous experiments have revealed interesting systematic natures of this phenomenon.

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. [ta**g**uta]→[**d**a**g**uta]), and (3) nonce words whose rendaku would result in a non-local violation of Lyman's Law (e.g. [tatsu**g**a]→[**d**atsu**g**a]). The comparison between the first 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.

[5] `https://osf.io/ym79p/?viewonly=ce17de5a39834ae397c44a19e74db082`. We fully acknowledge that adapting the open science policy is not 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 the problem.

2.1.2 Stimuli

Table 1 shows the 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).

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.

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

	No violation	Local violation	Non-local violation
/t/	[tamuma]	[taguta]	[tatsuga]
	[tatsuka]	[tozumi]	[tesago]
	[taɾuna]	[teguɾa]	[tekibi]
	[tonime]	[tazanu]	[takuga]
	[tekeha]	[tegesa]	[tekoʑi]
	[tokeho]	[toboɸu]	[teçigi]
/k/	[kimane]	[kidaku]	[kitebe]
	[kikake]	[kobono]	[kotiba]
	[kotona]	[kabomo]	[kaɕido]
	[kumise]	[kedeɾe]	[kutɕibo]
	[konihe]	[kuʑiha]	[kesodo]
	[kehaɾo]	[kozana]	[katsuba]
/s/	[samaɾo]	[sabaɾe]	[sokabo]
	[sokato]	[sogeha]	[sohogi]
	[sutane]	[sobumo]	[sukabi]
	[samohe]	[sadanu]	[suhode]
	[soɾise]	[sodoka]	[satage]
	[sateme]	[sudaɸu]	[sokebi]
/h/	[honaɾa]	[hobasa]	[hokida]
	[çinumi]	[hazuke]	[hekazu]
	[honiko]	[hogoɾe]	[hetado]
	[hakisa]	[çigiɾo]	[hategi]
	[heɾaho]	[ɸuzumo]	[çisuda]
	[çihonu]	[hedeno]	[ɸuhode]

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 (which used to be 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 SurveyMoneky, 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 were collected from Keio University, who earned an extra credit for completing the experiment (they are all in their early twenties)—from this pool of data, we had to exclude the data from 17 students, because they were either a non-native 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 analyses.

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.

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; a sample question is thus, "given a nonce word [saɾita], when it is combined with [nise], which form sounds more natural, [nise-saɾita] or [nise-zaɾita]?"

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 (see above), 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 answer 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 as native words (see Vance 1979 and Zuraw 2000 for previous studies which used this method). 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] vs. [nise-zaɾita] example to make sure that they understood the task.

2.1.5 Statistical analyses

For statistical analyses, we fit a Bayesian mixed effects logistic regression model, using the `brms` package (Bürkner 2017) and R (R Development Core Team 1993–) (for accessible introduction to Bayesian modeling, see e.g. Franke & Roettger 2019; Kruschke 2014; Kruschke & Liddell 2018; McElreath 2020; Vasishth et al. 2018). Bayesian analyses take both prior distribution (if any) and the obtained data into consideration and produce a range of possible values (=posterior distributions) for each parameter that we would like to estimate. One advantage of Bayesian analyses 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 access with how much confidence we can believe in a null effect (Gallistel 2009). Since Kawahara (2012) obtained a "statistically non-significant result", this was an important advantage of using Bayesian analyses 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 estimate parameter. If that interval does not include 0, we can interpret that effect to be meaningful/credible. However, with Bayesian analyses, we do not need to commit ourselves to a "meaningful" vs. "non-meaningful" dichotomy, as in a frequentist "significant" vs. "non-significant" 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 deployed 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. non-local 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 non-local 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 be /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.

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 run 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 circles are the averages in each condition. Abstracting away from the differences among the four segments, the three conditions resulted in the following rendaku application rates from left to right: (1) 60.8% (2) 32.4% (3) 41.6%. The markdown file available at the OSF repository provide segment-specific average values.

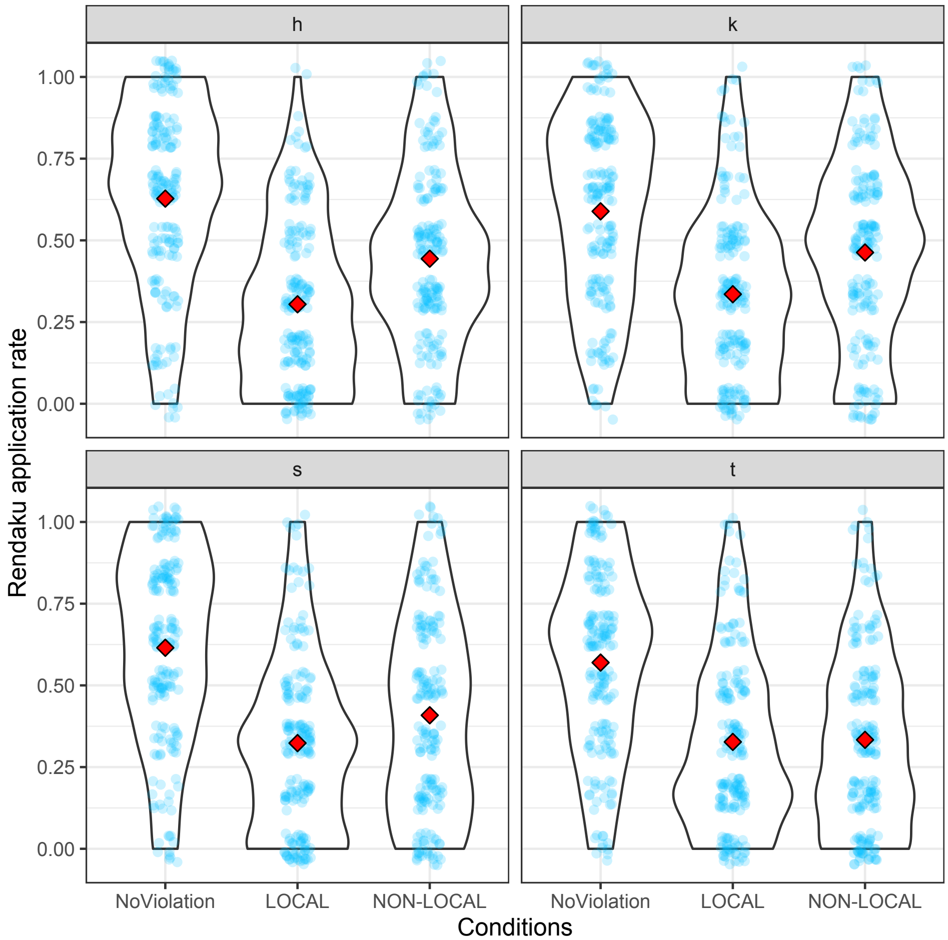

Figure 1: The comparison between the three critical conditions, with each facet showing a different segment type. Transparent circles, which represent averaged responses from each participant, are jittered slightly to avoid overlap. The red triangles show the averages within each violion.

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 non-local 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), the top) was very credible, supporting the psychological reality of Lyman's Law.

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

		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. non-local	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. non-local	-0.04	0.31	[-0.65, 0.57]
	/s/:local vs. non-local	-0.24	0.32	[-0.87, 0.38]
	/t/:local vs. non-local	-0.69	0.32	[-1.31, -0.07]

Most interestingly for the case at hand, the main effect of the difference between the local violation and non-local violation ((c), the 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 posterior 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 non-local Lyman's Law condition induced higher rendaku responses than the local Lyman's Law condition.

The results show that $p(\beta > 0)$ is 0.503 for /t/, 0.996 for /k/, 0.970 for /s/ and 0.998 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 is 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 inter-speaker differences. Among the speakers who participated in the current experiment, how general 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 non-local violation condition. Those dots above the diagonal axis are those speakers who are sensitive to a locality effect in the expected direction, and there were many of them. However, there are a number of participants who are around the diagonal axis, who are not sensitive to the locality effect. And rather surprisingly, there were also those who are below the diagonal axis, who represent an "anti-locality" effect. Nevertheless, there are many more speakers who showed an expected locality effect than those who showed an anti-locality effect (113 vs. 51; 16 had the equal number of yes-rendaku responses between the two conditions).

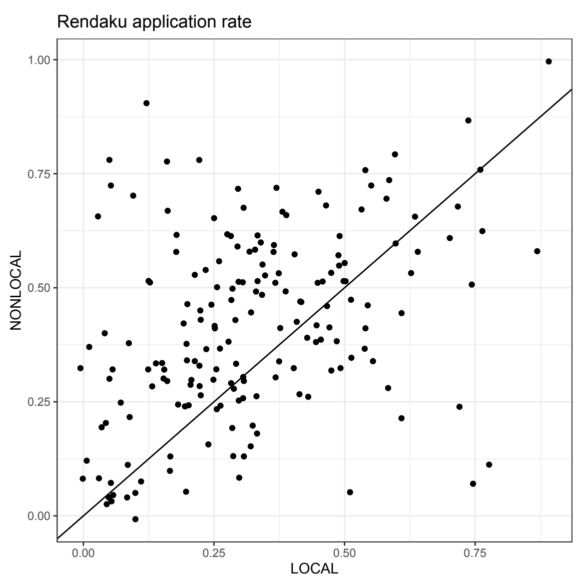

Figure 2: The comparison between the local violation condition and the non-local violation condition by each speaker (Experiment 1).

Given that Vance (1979) found 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 (1979) and thus may not be too surprising. In this sense too, we replicated the results by Vance (1979) with a much larger number of participants.

2.3 Discussion

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 non-local 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 which cannot be learned from the lexical patterns of rendaku and Lyman's Law alone (see Berent 2013, Coetzee 2009, Shinohara 1997, Gallagher 2013, 2016, Wilson 2006 and 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."[6]

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 non-local violation of Lyman's Law (e.g. [**d**aijamoni**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 non-local 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' grammar, 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.

Some more questions arise from the current results, not of all which we can answer in this

[6] Here is an admittedly post-hoc explanation of how such anti-locality pattern may have arisen in the current experiment. An anonymous reviewer pointed out that in the non-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], becomes similar to existing compounds like [datsu-goku] 'prison break', [datsu-bou] 'hats off', [datsu-zoku] 'unwolrdliness', 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 twords 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 to be an interesting one, examining this post-hoc speculation in a full detail needs be executed in a future study.

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 non-trivial degree of interspeaker variability, as in Figure 2; neither are we able to offer a solid explanations regarding why there are speakers who show the "anti-locality" effect (though see footnote 6 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 non-local condition. We find the last question to be the most important one to address, partly because it led Vance to consider his old results to an artifact of uncontrolled factors (Vance 2022). 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 (2012) lacked a sufficient statistical power, i.e., the 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, that is with N that is comparable to that of Experiment 1.

3.1 Method

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, the limitation of which is that we can include only up to 50 questions. Therefore, we limited ourselves to two segments /k/ and /s/, 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' and 1 was labeled was 'very unnatural' other points on the scale were not labelled). For statistical analyses, we used a Baysian *ordinal* logical 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, with the following numbers of speakers in each age-group: 3 (18-19 years old), 23 (20-29 years old), 30 (30-39 years old), 39 (40-49 years old), 66 (50-59 years old) and 26 (above 60 years old).

3.2 Results

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 non-local violation were rated as intermediate. The grand averages from the left to right were: 3.01, 2.68 and 2.79.

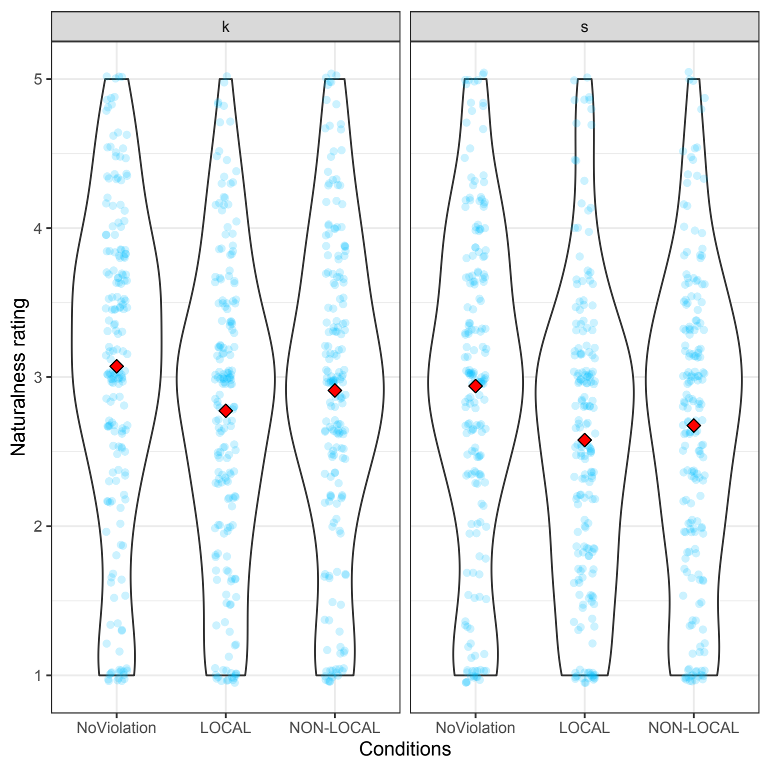

Figure 3: The comparison between the three critical conditions in naturalness ratings (Experiment 2).

The model summary of the results in Experiment 2 appears in Table 3. The 95% CrI for the segmental difference (coefficient (b)) includes 0, although the distribution is leaning toward the negative, 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), the 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 the Lyman's Law were clear for both segments: for /k/, ($p(\beta > 0) = 0.99$ and for /s/ as well, ($p(\beta > 0) = 0.99$. These results are compatible with the results of Kawahara (2012).

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

		β	error	95% CrI
(a) (baseline = /k/, local)				
intercept[1]		-2.44	0.25	[-2.92, -1.95]
intercept[2]		-0.50	0.25	[-0.98, -0.01]
intercept[3]		1.63	0.25	[1.15, 2.11]
intercept[4]		3.79	0.25	[3.30, 4.29]
(b) segment		-0.47	0.24	[-0.94, 0.00]
(c) condition	no-violation vs. local	0.78	0.25	[0.28, 1.28]
	local vs. non-local	0.34	0.24	[-0.13, 0.82]
(d) interactions	seg:no-violation vs. local	-0.13	0.33	[-0.79, 0.53]
	seg:no-violation vs. local	0.12	0.34	[-0.55, 0.77]

The 95% CrI for the difference between the local and non-local violation conditions (coefficient (c), the bottom) include 0, but it is leaning toward positive values, suggesting that the non-local violation condition tended to induce more natural responses than local responses. In terms of the probabilities of the β-coefficients being in the expected direction in the posterior distributions, the difference between the local violation and non-local violation at the baseline level (=/k/) was $p(\beta > 0) = 0.92$. The locality comparison at the level of /s/ was $p(\beta > 0) = 0.81$. Thus, we are at least 80% positive that the local and non-local 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 those who show an anti-locality effect. As with Experiment 1, we do observe that both types of speakers exist, but more speakers show a locality effect than an anti-locality effect, hence the overall results in Figure 3 (93 vs. 57 speakers; 37 speakers showed the same average rating between the two conditions).

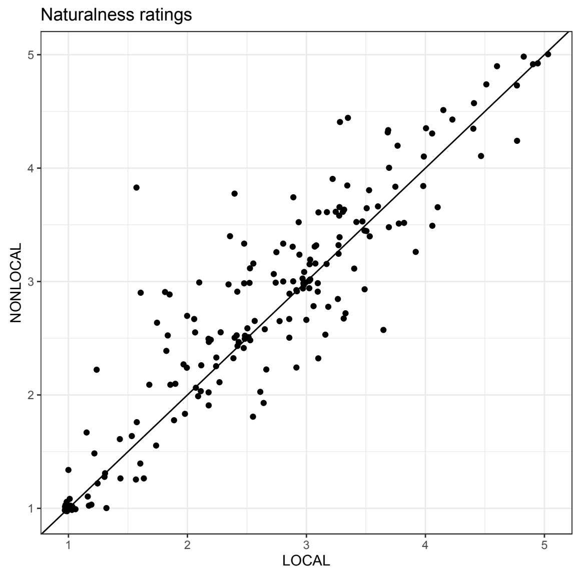

Figure 4: The comparison between the local violation condition and the non-local violation condition by each speaker (Experiment 2).

3.3 Discussion

We thus observe at least modest evidence (i.e. 80%–90% confidence) that the local violation of Lyman's Law and the non-local 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 (2012) did observe a trend in the expected direction and that the sizes of differences were almost identical between Kawahara (2012) and the current experiment (2.76 vs. 2.86 = 0.10 in Kawahara 2012 and 2.68 vs. 2.79 = 0.11 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 "non-significant." The use of Bayesian analyses allowed us to see how confident we can be about the difference between the local condition and the non-local condition, without being bound to the "significant vs. non-significant" dichotomy.

Having said these, 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 once (Kerr 1998), having seen the results of Experiment 2 prompted us to see what would happen if we run a Bayesian analysis to the data obtained by Kawahara (2012). Explicitly bearing in mind that this is a post-hoc analysis, 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 on 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 non-local condition violation, $p(\beta > 0) = 0.938$ 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.

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 is not 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 re-examine 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 study 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 follow-up studies.

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Conflicts of interest

We declare no conflicts of interest.

Availability of data and material

The data are available at
`https://osf.io/ym79p/?viewonly=ce17de5a39834ae397c44a19e74db082`

Code availability (software application or custom code)

The code is also available at
`https://osf.io/ym79p/?viewonly=ce17de5a39834ae397c44a19e74db082`

Authors' 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.

Ethics approval

The current experiments were conducted with an approval from the authors' institute.

Consent to participate

The participants read the written 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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