The phonetics of obstruent geminates, *sokuon*[*]

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Abstract

This chapter provides an overview of the phonetic aspects of Japanese obstruent geminates, referred to as *sokuon* in the traditional Japanese literature. This chapter starts by reviewing the acoustic correlates of Japanese geminates. The primarily acoustic correlate has been shown to be constriction duration, accompanied by various secondary cues. Then the chapter turns to the effect of manner on geminates, focusing on fricative geminates and voiced stop geminates. The chapter also compares the acoustic features of Japanese geminates with those found in other languages. Then the chapter discusses the perception of geminates, reviewing several perceptual cues for Japanese geminates, again in comparison with other languages. The final topic of the chapter is articulatory studies of geminates. Throughout I raise issues that require future experimentation, and the final section of the chapter lays out more issues that are not covered in the main body of the paper.

Contents

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1 Introduction

Japanese has a phonemic contrast between short and long consonants, as exemplified by minimal pairs like [kata] 'frame' vs. [katta] 'bought' and [hato] 'dove' vs. [hatto] 'hat'. Short consonants are generally referred to as "singletons" and long consonants are referred to as "geminates". In traditional Japanese terms, obstruent geminates are called *sokuon*: its coda part is represented with /Q/, and it is also represented with "small tsu" in the Japanese orthographic system. On the other hand, the coda portion of nasal geminates is called *hatsuon* (represented with /N/), but this chapter focuses on obstruent geminates.[1] (In the rest of the paper, I use the term "geminates" to mean "obstruent geminates" or *sokuon*.) This chapter provides an overview of the acoustic characteristics of Japanese geminates and their perceptual cues.[2]

2 The acoustic characteristics of geminates in Japanese

2.1 The primary acoustic correlate: constriction duration

Japanese is famously a mora-timed language (Warner & Arai 1999 for a review, see also the chapter on mora-timing), and geminates are moraic; for example, disyllabic words containing a geminate like [katta] 'bought' and [hatto] 'hat' contains three moras. Reflecting this moraic nature, geminate consonants in Japanese involve long consonantal constriction. In other words, the primary acoustic correlate of a singleton-geminate distinction is a difference in constriction duration—closure duration for stops and frication duration for fricatives (In this paper, I use the term "duration" to refer to phonetic measures, and "length" to refer to a phonological contrast; I use the term "constriction" as a cover term for stop closure and narrow aperture for fricatives).[3]

Before proceeding to the discussion of the actual difference, one remark about what it is meant by "primary" is in order, because the concept of "being primary" can mean several different notions. A primary acoustic correlate could mean an acoustic parameter that is invariant across speakers, speech styles, phonological contexts, or even across languages, and/or that it constitutes

[1] Approximants (liquids and glides) do not become geminates in Japanese, except in emphatic forms (e.g. [kowwai] 'very scary'). See Aizawa (1985), Kawahara (2001), and section 5.3 for the non-structure preserving nature of this emphatic gemination in Japanese.

[2] A topic that this paper does not cover, primarily due to limitation of the author's expertise, is L2 learning of Japanese geminates. I would like to direct the readers to the following references: Han (1992); Motohashi-Saigo & Hardison (2009); Oba et al. (2009); Tajima et al. (2008), the papers in a special issue of *Onsei Kenkyuu* 11:1 (Kubozono, 2007), those cited therein, and the chapter on L2 phonology. Another topic that this chapter does not cover is a gemination pattern found in the process of loanword adaptation (e.g. [bakku] 'back'), which arguably has a perceptual basis (e.g. Takagi & Mann 1994). See the chapter on the phonology of geminates and the chapter on loanword phonology on this phenomenon.

[3] For affricates, the primary acoustic correlate seems to lie in the difference in the closure duration, not in the frication duration (Oba et al., 2009).

a primary perceptual cue which dominates other secondary cues (Lahiri & Hankamer, 1988) so that secondary cues are tangible only when the target stimuli are ambiguous, distributing around a range that is not found in natural speech (Hankamer et al., 1989; Pickett et al., 1999). See Abramson & Lisker (1985); Stevens & Blumstein (1981); Stevens & Keyser (1989); Whalen et al. (1993) for general discussion, and Abramson (1992); Hankamer et al. (1989); Idemaru & Guion (2008); Lahiri & Hankamer (1988); Pickett et al. (1999); Ridouane (2010) for the discussion of "primacy" in the context of length distinctions. Ridouane (2010) argues that cross-linguistically, differences in constriction duration are the most consistent acoustic correlates of singleton-geminate contrasts.

With this said, the primary acoustic correlate of Japanese geminates is that geminate consonants are characteristically longer than singleton consonants. Figures 1 and 2 show illustrative waveforms and spectrograms of a singleton [t] and a geminate [tt] in Japanese (the time scale is the same, 300ms). As we can see, the geminate [tt] has a longer closure than the singleton [t].

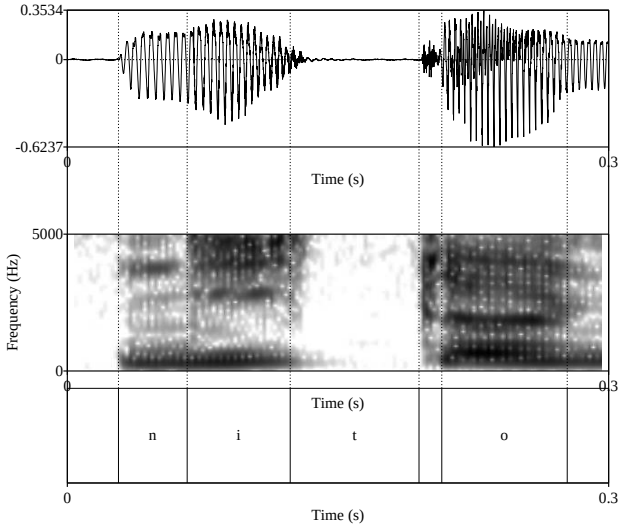

Figure 1: A singleton [t]

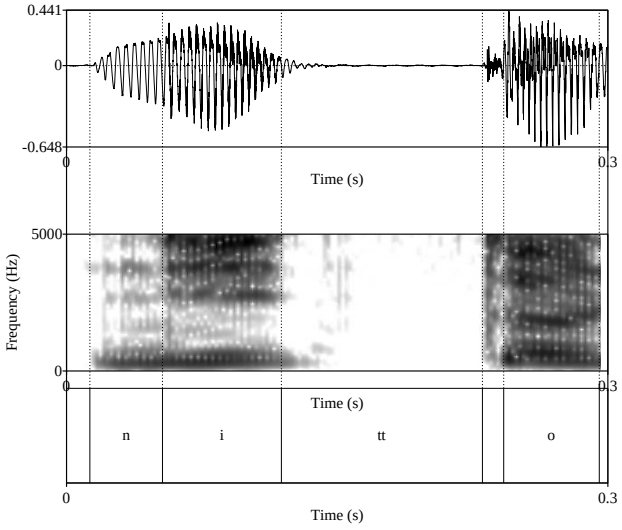

Figure 2: A geminate [tt]

Many acoustic studies have investigated the durational properties of singleton-geminate contrasts in Japanese, and Table 1 summarizes their findings. This summary shows that geminates are generally at least twice as long as corresponding singletons, and can sometimes be as three times as long, regardless of the place of articulation or voicing status of the consonants (though see section 2.3).

2.2 Secondary acoustic correlates

As with many other phonological contrasts, a singleton-geminate contrast is acoustically realized not only in terms of constriction duration, but also manifests itself in multiple acoustic dimensions (multiplicity of acoustic correlates of phonological contrasts: e.g. Kingston & Diehl 1994).

2.2.1 Other durational correlates

In Japanese, vowels are longer before geminates than before singletons (Campbell, 1999; Fukui, 1978; Han, 1994; Hirose & Ashby, 2007; Idemaru & Guion, 2008; Kawahara, 2006a; Ofuka, 2003; Port et al., 1987; Takeyasu, 2012).[4] Port et al. (1987) found for example that [ɯ] is on average 68ms before singleton [k] and 86ms before geminate [kk]. Kawahara (2006a) similarly found that vowels before voiceless singletons are on average 36.9ms while those before voiceless geminates are 53.4ms. Furthermore, some studies even found that in C_1VC_2V structure, C_1 is longer when C_2 is a geminate than when C_2 is a singleton (Han, 1994; Port et al., 1987) (cf. Takeyasu 2012 who found the opposite pattern; Hindi shows the same lengthening pattern: Ohala 2007).

On the other hand, following vowels are shorter after geminates than after singletons (Campbell, 1999; Han, 1994; Idemaru & Guion, 2008; Ofuka, 2003). Han (1994) found the shortening of following materials (sometimes including word-final moraic nasals) by 9ms after geminates. In Idemaru & Guion (2008), the mean duration of the following vowel is 63ms after geminates and 76ms after singletons.

Finally, one may expect that VOT (Voice Onset Time) would be longer for geminate stops than for singleton stops, because longer closure would result in higher pressure build-up behind the stop occlusion. However, it does not seem to be true: VOT is slightly shorter for geminates than for singletons in a study reported by Han (1994), and the relationship is inconsistent in other studies (Hirata & Whiton, 2005; Homma, 1981). See Kokuritsu-Kokugo-Kenkyuujo (1990) for the data on the intraoral air pressure rise in Japanese consonants, which indeed shows that geminates do not involve higher intraoral air pressure rise.

2.2.2 Other, non-duratinal, acoustic correlates

Several studies, most recently Idemaru & Guion (2008) and Kawahara (2006a), investigated other non-durational, acoustic correlates of a singleton-geminate contrast in Japanese. The findings are summarized in Table 2.

[4] Vowels are also longer in closed syllables before a so-called moraic nasal (or *hatsuon*) than in open syllables (Campbell, 1999), indicating that this lengthening is due to a general, syllable-based phenomenon. The pre-geminate lengthening can also block otherwise productive high vowel devoicing between two voiceless consonants (Han 1994; Takeyasu 2012; see also the chapter on devoicing).

Table 1: Closure duration differences between singleton and geminate stops in Japanese. Duration measures are in mili-seconds. SD=standard deviation; MoE=margin of error for 95% confidence intervals

Sources	Sing duration	Gem duration	Ratio	Note
Han (1962)	–	–	2.6 - 3.0	based on small N
Homma (1981)	[p]: 77	[pp]: 183	2.38	4 speakers
	[b]: 55	[bb]: 159	2.89	
	[t]: 62	[tt]: 170	2.74	
	[d]: 35	[dd]: 144	4.11	
	[k]: 61	[kk]: 175	2.87	
	[g]: 41	[gg]: 134	3.27	
Beckman (1982)				(SD), 5 speakers
	[k]: 89 (17)	[kk]: 195 (32)	2.25	VOT included
	[k]: 64 (15)	[kk]: 171 (32)	2.79	VOT excluded
Port et al. (1987)				(SD), 10 speakers
	[k]: 65 (12)	[kk]: 149 (25)	2.29	ɯ_ ɯ
	[k]: 66 (14)	[kk]: 146 (28)	2.21	a _ ɯ
Han (1994)				(SD), 10 speakers
(see also Han 1992)	[p]: 76.3 (5.6)	[pp]: 195.9 (21.9)	2.57	sɯ_ai
	[p]: 72.9 (9.7)	[pp]: 205.4 (29.9)	2.82	sɯ_ori
	[t]: 71.5 (7.4)	[tt]: 192.3 (27.2)	2.69	i_e
	[t]: 53.5 (8.0)	[tt]: 166.6 (24.1)	3.11	kí_e
	[t]: 57.9 (10.2)	[tt]: 174.5 (21.5)	3.01	ʃi_ei
	[t]: 52.7 (8.0)	[tt]: 170.9 (25.8)	3.24	ki_e
	[t]: 68.2 (9.0)	[tt]: 189.8 (28.5)	2.78	i_a
	[k]: 63.5 (8.5)	[tt]: 178.2 (22.5)	2.81	yo_a
	[k]: 57.5 (8.5)	[tt]: 175.8 (30.9)	3.06	ʃi_e
	[k]: 79.4 (6.6)	[kk]: 198.7 (24.6)	2.50	ha_eN
Kawahara (2006a)	vls: 59.9 (2.1)	vls: 128.6 (3.1)	2.15	(MoE), 3 speakers
	vcd: 42.3 (1.7)	vcd: 113.1 (3.0)	2.67	
Hirose & Ashby (2007)	vls: 60.5	vls: 114.2	1.89	3 speakers
	vcd: 44	vcd: 108	2.45	
Idemaru & Guion (2008)	69 (28)	206 (45)	2.99	(SD), 6 speakers all stop consonants

Table 2: A summary of other, non-durational, acoustic correlates of Japanese geminates. F=Fukui (1978), I&G=Idemaru & Guion (2008), O=Ofuka (2003), K=Kawahara (2006a)

	Patterns	References
Intensity	The mean intensity difference is larger across geminates.	I&G, O
F0	Accentual F0 drop is larger across geminates.	I&G, O, K
F0	Pitch falls toward geminates.	F
F1	Lower after geminates.	K
Spectral tilt	H1-A1 smaller for geminates after geminates (i.e. vowels are creakier).	I&G

2.2.3 The search for invariance

One general research program in phonetics is the search for invariance (Stevens & Blumstein, 1981). The issue addressed in this program is whether, for each phonological distinction, there exists any acoustic correlate that is invariant across phonological contexts, individual speakers, and speech styles, etc, and if yes, what they are. This issue is particularly important for a singleton-geminate contrast, because geminates in fast speech styles can be shorter than singletons in slow speech styles (Hirata & Whiton, 2005; Idemaru & Guion-Anderson, 2010).[5] Usually proposals for invariant measures take the form of a relationship between more than one acoustic parameter. The general idea behind these studies on phonological contrasts based on durations is rate normalization, in which listeners normalize the duration of incoming acoustic signal according to the speech rate, which can be inferred from the duration of other intervals (Miller & Liberman, 1979; Pickett & Decker, 1960). For example, when a preceding vowel sounds short, a listener may conjecture that the speaker is speaking fast, and as a result even a short interval may be interpreted as long.[6]

For a singleton-geminate contrast, several relational correlates have been proposed as an invariant measure that distinguishes between singletons and geminates across different speech rates. Hirata & Whiton (2005) recorded various disyllabic tokens of singletons and geminates in nonce words and real words in three speech styles (slow, normal, fast), and considered three measures: raw closure duration, C/V ratio (the ratio between the target consonant and the preceding vowel), and C/W(ord) ratio. Hirata & Forbes (2007) further considered two more measures: V-to-V interval (i.e. added durations of preceding vowel, constriction and VOT) and VMora (V-to-V interval

[5]It has been observed in other languages (Italian and Persian) (Hansen, 2004; Pickett et al., 1999) that geminates are more susceptible to change in duration due to speech rate than singletons are. This asymmetry seems to hold in the Japanese data as well (Hirata & Whiton, 2005; Idemaru & Guion-Anderson, 2010).

[6]An alternative theory is auditory durational contrast in which an interval is (more or less automatically) rendered to sound longer next to a shorter interval by a general auditory mechanism (a.k.a. "durational contrast"), which is not specific to speech (Diehl & Walsh, 1989; Kluender et al., 1988). It is beyond the scope of this paper to compare these two theories (see Diehl et al. 1991; Fowler 1990, 1991, 1992; Kingston et al. 2009 for further discussion on this debate).

divided by mean mora duration). Idemaru & Guion-Anderson (2010) tested yet a few more relational measures: C/V_1, C/C_1V_1, C/V_2, $C/(C+V_2)$ (where C is the target consonant, C_1 and V_1 are the preceding consonant and vowel, and V_2 is the following vowel) in addition to those already tested by Hirata & Whiton (2005) (raw closure duration and C/W ratio). After recording their own various tokens of singletons and geminates in three speaking rates, for each measure, they tested classification accuracy percentages based on raw values as well as z-transformed (normalized) values within each speaker. Discriminant analyses were used, for each proposed measure, to calculate how many percentages of tokens are accurately classified as a member of the intended category. The classification accuracy percentages of all the measures in these studies are summarized in Table 3.[7]

Table 3: A summary of classification accuracy percentages in the three studies cited in the text. See text for explanations of each measure

Hirata & Whiton (2005)	
raw C duration:	82.2% (nonce words) and 81.4% (real words)
C/V_1 ratio:	92.1% (nonce words) and 91.3% (real words)
C/W	98% (nonce words) and 95.7% (real words)
Hirata & Forbes (2007)	
V-to-V interval	75.5%
VMora	99.6%
Idemaru & Guion-Anderson (2010)	
C/V_1	83.7% (raw) and 85.5% (normalized)
C/C_1V_1(mora)	92.6% (raw) and 94.5% (normalized)
C/V_2	94.1% (raw) and 94.9% (normalized)
$C/(C+V_2)$	92.3% (raw) and 93.0% (normalized)
C/Word	96.3% (raw) and 96.8% (normalized)
raw C duration	87.2% (raw) and 88.3% (normalized)

One thing that is clear from Table 3 is that relational measures generally classify singletons from geminates better than raw durational values. Which relational measure best cross-classifies Japanese singletons from geminates is an interesting topic for on-going and future research.

Another important issue is its perceptual relevance—or reality—of these acoustic measures. For example, Idemaru & Guion-Anderson (2010) followed up their acoustic study with a perception test, which showed that while preceding mora (CV) duration significantly affects the perception of geminacy, the following materials (C/V_2 ratio) do so only marginally, despite that ratios

[7]Other relational invariant measures proposed for length contrasts in other languages include C/V_1 ratio for Italian (Pickett et al., 1999), vowel to rhyme duration ratio for Icelandic (Pind, 1986) (in which long vowels and geminates are (more or less) in complementary distribution), and the ratio of the closure duration to the syllable duration in Persian (with some further complications) (Hansen, 2004).

involving these two factors yielded comparable accuracy percentages in production (see Table 3). See also Amano & Hirata 2010; Otaki 2011 and section 3.2 for further discussion on the relationship between production and perception, especially in terms of contextual effects on the perception of length contrasts.

2.3 Manner effects

One issue that received relatively less attention in the previous literature is the comparisons of different manners of geminates in Japanese. Most previous acoustic studies on Japanese have investigated oral stops (Beckman, 1982; Han, 1992, 1994; Hirata & Whiton, 2005; Hirose & Ashby, 2007; Homma, 1981; Idemaru & Guion, 2008; Kawahara, 2006a), although some studies did measure geminates of various manner types (e.g. Han 1962 who measured oral stops and nasals). Other languages that have been studied in this light include Italian (Faluschi & Di Benedetto, 2001; Giovanardi & Di Benedetto, 1998; Mattei & Di Benedetto, 2000; Payne, 2005), Cypriot Greek (Tserdanelis & Arvaniti, 2001), Guinaang Bontok (Aoyama & Reid, 2006), Buginese, Madurese, and Toba Batak (Cohn et al., 1999).

2.3.1 Fricative geminates

Japanese allows both stops and fricatives to contrast in geminacy. One complication is that singleton fricatives are generally longer than singleton stops in the first place in Japanese (Beckman, 1982; Campbell, 1999; Port et al., 1987; Sagisaka & Tohkura, 1984) and other languages (Lehiste, 1970). As a result, singleton/geminate duration ratios are smaller for fricatives than for stops. Table 4 reports unpublished data collected by the author based on three female Japanese native speakers. All speakers were in their twenties at the time of recording, and the recording took place in a sound-attenuated room. Each target sound was pronounced in a (nonce) word frame [ni_o], itself being embedded in a frame sentence. All three speakers repeated 10 repetitions of all tokens.[8]

Table 4 shows the results of duration measurements. We can first observe that duration ratios are highest for voiced stops than voiceless stops (see also Homma 1981 and Hirose & Ashby 2007 for the same finding), which are also generally higher than for fricatives (except for [ç] and [h]).[9] The phonological importance of this difference between stop pairs and fricative pairs is that the length contrast may be less perceptible for fricatives than for stops. The lower perceptibility

[8] I am grateful to Kelly Garvey and Mel Pangilinan for their help with this acoustic analysis.

[9] This study also found that the duration ratio for [p] is smaller than that of [t] and [k]. This lower ratio may be related to the fact that length is not contrastive for [p] in the native phonology in Japanese (see Itô & Mester 1995, 1999 and the chapter on phonological lexicon and mimetics). One puzzle, however, is why voiced stops have high duration ratios despite the fact that they are not contrastive in native Japanese phonology (Itô & Mester, 1995, 1999). See also Engstrand & Krull (1994) for the relationship between the functional load of length contrasts and their phonetic realizations. A full consideration on this relationship should be explored in future studies.

Table 4: The effects of manner of articulation on the duration of singletons and geminates in Japanese (margin of error (MoE) for 95% confidence intervals)

segment	singleton	geminate	ratio
[p]	77.3 (7.8)	129.6 (8.1)	1.68
[t]	55.5 (4.6)	124.4 (7.3)	2.24
[k]	67.3 (7.1)	128.7 (7.1)	1.91
[b]	53.1 (3.8)	131.4 (8.8)	2.47
[d]	36.6 (1.9)	116.0 (10.4)	3.16
[g]	52.1 (3.7)	115.0 (13.2)	2.20
[ɸ]	83.5 (4.8)	144.7 (7.4)	1.73
[s]	83.2 (4.6)	134.5 (7.0)	1.62
[ʃ]	85.9 (5.7)	138.4 (7.3)	1.61
[ç]	63.4 (2.5)	132.0 (6.2)	2.08
[h]	72.2 (4.2)	143.7 (6.4)	1.99

may lead to a diachronic neutralization (Blevins, 2004) and/or avoidance of fricative geminates in synchronic phonological patterns (Kawahara, 2006b) based on a principle of contrastive dispersion to avoid contrasts that are not very well perceptible (Flemming 2004 and references cited therein).

2.3.2 Voiced obstruent geminates

The effect of voicing on geminates is no less interesting. The native phonology of Japanese does not allow voiced obstruent geminates (Itô & Mester, 1995, 1999; Kuroda, 1965). The lack of voiced obstruent geminates perhaps has its roots in its aerodynamic difficulty (Ohala 1983, and more references cited in Kawahara 2006a). For voiced stops, the intraoral air pressure goes up behind oral stop closure; this rise in the intraoral air pressure makes it difficult to maintain the airflow required for vocal fold vibration. For voiced fricatives, the intraoral airpressue must rise to create frication, which again makes it difficult to maintain the transglottal air pressure drop. Perhaps for these reasons (synchronically or diachronically), Japanese native phonology does not allow voiced geminates.

However, gemination found in the context of loanword adaptation resulted in voiced stop geminates (e.g. Katayama 1998; Kubozono et al. 2008; Shirai 2002); e.g. [heddo] 'head' and [eggɯ] 'egg'. Nevertheless, due to the aerodynamic difficulty, voiced geminate stops are generally "semi-devoiced" in Japanese. All three speakers recorded in Kawahara (2006a) show this semi-devoicing. Figures 3 and 4 illustrate this difference between singletons and geminates: for singleton [g], closure voicing is fully maintained, while for geminate [gg], closure voicing stops in the middle of

its whole closure.[10] In Kawahara (2006a), on average, closure voicing is maintained only about 40% of the whole closure. Hirose & Ashby (2007) replicate this finding and showed that voiced Japanese geminates have only 47% of closure voicing.

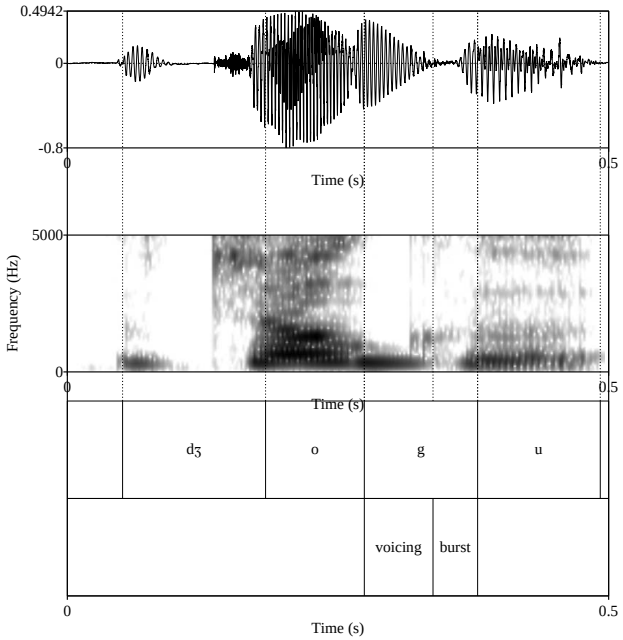

Figure 3: A singleton [g]

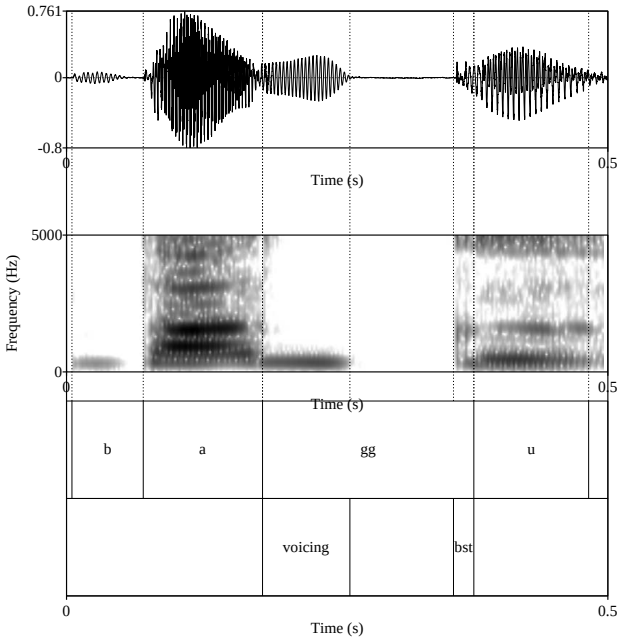

Figure 4: A geminate [gg]

As far as I know, there is no study on the phonetic implementation on voiced geminate fricatives in Japanese—this is a topic which is worth pursuing in a future study.

One notable aspect of this semi-devoicing of geminates is that the following, word-final high vowels after "semi-devoiced" geminates (e.g. [egg̊ɯ]) do not devoice, even though the vowels are preceded by a voiceless interval (Hirose & Ashby, 2007). The lack of high vowel devoicing shows that the (semi-devoiced) voiced geminates are still phonologically voiced, and that high vowel devoicing is conditioned by phonological, rather than, phonetic factors. See the chapter on vowel devoicing for further discussion on this debate.

The semi-devoicing of geminates is found in other languages (e.g. (Tashlhiyt) Berber: Ridouane 2010), but is not universal despite the fact that it presumably arises from the physical, aerodynamic difficulty (Ohala, 1983). Cohn et al. (1999) show for example that Buginese, Madurese, and Toba Batak all maintain voicing throughout the geminate closure; Egyptian Arabic is another language which has fully voiced geminates (Kawahara, 2006a), and Lebanese Arabic shows high percentages of voicing maintenance in medial, non-final, positions (Ham, 2001). Cohn et al. (1999)

[10] These tokens are based on new recordings made in 2010.

speculate that speakers resort to extra articulatory maneuvers like larynx lowering and cheek expansion to deal with the aerodynamic challenges; these articulatory gestures expand the size of oral cavity, thereby lowering the intraoral pressure, providing the transglottal air pressure drop necessary for voicing (see Ohala 1983). The reason that Japanese speakers do not deploy such articulatory strategies—at least not to the extent that geminates are fully voiced—may be that voiced obstruent geminates are historically relatively new, and therefore the functional load of a voicing contrast in geminates is low, the contrast being contrastive only in loanwords (Itô & Mester, 1995, 1999); i.e. there are not many minimal pairs. It would thus be interesting to observe whether speakers of future generations would start producing fully-voiced geminates, once the voicing contrast in geminate becomes more widespread in the Japanese lexicon. Moreover, a further cross-linguistic comparison is warranted to explore the relationship between how voiced stop geminates are implemented and how the particular phonetic implementation patterns affect their phonological patterns (see Kawahara 2006a for discussion).

2.4 Comparison with other languages

2.4.1 Constriction duration

I have already mentioned a few differences and similarities between Japanese geminates and those found in other languages, but we now turn our attention to a more detailed comparison of Japanese with other languages. As reviewed in section 2.1, Japanese geminates are acoustically characterized by long constriction duration, almost always twice as long as the corresponding singletons. Similarly, constriction duration is usually the primary acoustic correlate of a singleton/geminate contrast in other languages; e.g. (Lebanese) Arabic (Ham, 2001), Bengali (Lahiri & Hankamer, 1988), Berber (Ridouane, 2010), Bernese (Ham, 2001), Buginese (Cohn et al., 1999), Estonian (Engstrand & Krull, 1994), Finnish (Engstrand & Krull, 1994), Cypriot Greek (Tserdanelis & Arvaniti, 2001), Guinaang Bontok (Aoyama & Reid, 2006), Hindi (Ohala, 2007; Shrotriya et al., 1995), Hungarian (Ham, 2001), Italian (Esposito & Di Benedetto, 1999; Payne, 2005; Pickett et al., 1999), Madurese (Cohn et al., 1999), Malayalam (Local & Simpson, 1999), Pattani Malay (Abramson, 1987b), Persian (Hansen, 2004), Swedish (Engstrand & Krull, 1994), Swiss German (Kraehenmann & Lahiri, 2008), Toba Batak (Cohn et al., 1999), and Turkish (Lahiri & Hankamer, 1988) (see Ridouane 2010 for more languages and references).

One interesting cross-linguistic difference is the size of duration ratios between singletons and geminates; in Norwegian, for example, the ratio is much smaller than in Japanese (ranging from 1.22-1.38 in medial positions), and more substantial differences manifest themselves in the duration of preceding vowels (Fintoft, 1961) (although one should note that Fintoft measured only non-stop consonants; see section 2.3.1). In Buginese and Madurese, the geminate/singleton dura-

tion ratios are generally below 2 (Cohn et al., 1999). Generalizing this observation, Ham (2001) suggests that geminate/singleton duration ratios are smaller for syllable-timed languages than for mora-timed languages.

2.4.2 Other durational correlates

As discussed in 2.2.1, vowels are longer before geminates in Japanese. This observation may come as a surprise given a cross-linguistic tendency that vowels in closed syllables are often shorter than vowels in open syllables (Maddieson, 1985). Indeed many languages have shorter vowels before geminates than before singletons; e.g. Bengali (Lahiri & Hankamer, 1988), Berber (Ridouane, 2010), Italian (Esposito & Di Benedetto, 1999; Pickett et al., 1999), Hindi (Ohala, 2007; Shrotriya et al., 1995), Malayalam (Local & Simpson, 1999), and the three Polynesian languages studied by Cohn et al. (1999).

However, there are other languages that arguably show lengthening of vowels before geminates: Turkish,[11] Shinhara (although only one of the two speakers showed clear evidence: Letterman 1994) and Persian (Hansen, 2004) (although no direct statistical tests are reported). The existence of such languages shows that Japanese may not simply be a case of typological anomaly, but languages vary in whether geminates shorten or lengthen the preceding vowels. I will come back to this issue of this cross-linguistic difference in section 3.2 in relation to its perceptual relevance.

In some languages, there are no substantial differences in preceding vowel duration between singletons and geminates; e.g. Egyptian Arabic (Norlin, 1987), Lebanese Arabic (at least for short vowels) (Ham, 2001), Estonian (Engstrand & Krull, 1994), and Hungarian (Ham, 2001). In Cypriot Greek, there is slight tendency toward shortening before geminates, but this tendency is not very consistent (Tserdanelis & Arvaniti, 2001).

Finally, the lack of effect of a geminacy contrast on VOT in Japanese is paralleled in many languages including Buginese, Madurese, Toba Batak (Cohn et al., 1999), Bernese, Hungarian, Lebanese Arabic (Ham, 2001), Bengali (Hankamer et al., 1989), and Berber (Ridouane, 2010). Cypriot Greek has consistently longer VOT for geminates (Tserdanelis & Arvaniti, 2001), but Turkish shows shorter VOT for geminates (Lahiri & Hankamer, 1988).

2.4.3 Other, non-durational, acoustic correlates

Different languages seem to show different acoustic correlates to signal singleton-geminate contrasts (in addition to the durational correlates), as summarized in (1)-(6).

(1) Bengali (Hankamer et al., 1989)

[11] The difference is small and statistically not significant in Lahiri & Hankamer 1988; see also Jannedy (1995) for evidence that this lengthening applies to closed syllables in general, as in Japanese (see footnote 4).

a. RMS (Root Mean Square) amplitude of the following syllable is higher after singletons.

(2) Berber (Ridouane, 2010)

a. Geminates have higher amplitude during release.

b. Geminates show burst release more consistently than singletons.

(3) Italian (Payne, 2006)

a. Geminates involve more palatalized constriction than singletons.

b. Geminate stops involve more complete occlusion.

c. Geminates are associated with a laminal gesture; singletons are associated with an apical gesture.

(4) Hindi (Shrotriya et al., 1995)

a. F0 rises toward geminates in the preceding vowel.

b. Burst intensity is stronger (by about 10dB) for geminates.

(5) Malayalam (Local & Simpson, 1999)

a. Sonorant geminates show palatal resonance with higher F2.

b. The surrounding vowels differ in F1 and F2.

(6) Pattani Malay

a. The peak amplitude of initial vowels (with respect to the following vowel) is higher after word-initial geminates than after singletons (Abramson, 1987b, 1998).

b. Fundamental frequency of word-initial vowels is higher after word-initial geminates (Abramson, 1998).

c. First vowels are longer (with respect to the second vowels) after word-initial geminates (Abramson, 1998).

d. The slope of amplitude rise is steeper after word-initial geminates (Abramson, 1998).

So far Idemaru & Guion (2008) is the most extensive study looking for spectral correlates of geminacy contrasts in Japanese, and it is yet to be investigated whether the correlates listed in (1)-(6) would be found in Japanese. (The Pattani Malay pattern may be special because it involves cases of word-initial geminates.) However, it seems likely at this point that phonetic implementation patterns of singleton-geminate contrasts are language-specific, the only universal rule being that geminates are longer than singletons (Ham, 2001; Ridouane, 2010). A remaining task in the phonetic theory is how to model the universality and language-specificity of phonetic implementation patterns of length contrasts.

3 The perception of geminates

We now turn to the perception of a singleton-geminate contrast.

3.1 The primary cue: constriction duration

Many studies have shown that the longer the constriction, the more likely the target is perceived as a geminate. This effect has been shown to hold in many perception studies using Japanese listeners (Amano & Hirata, 2010; Arai & Kawagoe, 1998; Hirata, 1990; Fujisaki et al., 1975; Fukui, 1978; Kingston et al., 2009; Oba et al., 2009; Takeyasu, 2012; Watanabe & Hirato, 1985). As an example, Figure 5 reproduces the results of Kingston et al. (2009) in which closure duration was varied from 45ms to 165ms with 15ms increments (see the next section for the three vocalic contexts). We observe that geminate responses increase as closure duration increases.

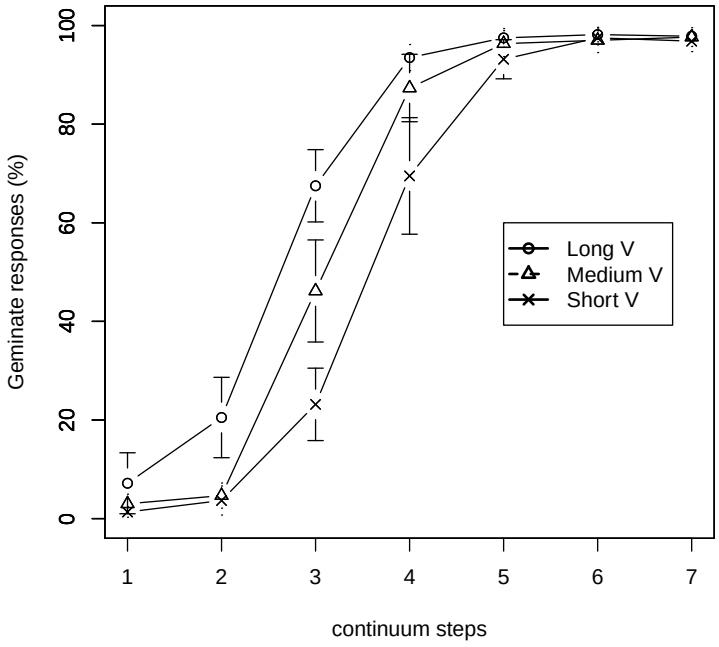

Figure 5: The effect of closure duration and the preceding vowel duration on the perception of geminates by Japanese listeners. Adapted from Kingston et al. (2009).

3.2 Contextual effects

More controversial than the effect of constriction duration is contextual effects. Fukui (1978) found that when the closure duration of an original singleton consonant is lengthened, it is almost always perceived as a geminate when the closure duration is doubled. On the other hand, shortening an original geminate did not result in a comparable shift in perception. The results show that closure duration is not the only cue for a length contrast (see also Abramson 1987a, 1992; Lisker 1958; Hankamer et al. 1989 for similar types of experiments on other languages (Bengali, Pattani Malay, Tamil, and Turkish) which found similar results (albeit to different degrees)).

As reviewed in section 2.2.1, vowels are longer before geminates, and therefore we expect that Japanese speakers would perceive a consonant more likely as a geminate after a longer vowel than after a shorter vowel. Several results indeed found a contextual effect in this direction (Arai & Kawagoe, 1998; Kingston et al., 2009; Ofuka, 2003; Ofuka et al., 2005; Takeyasu, 2012). This contextual effect is illustrated in Figure 5 in which listeners judged more of the continuum as geminates after longer vowels.

On the other hand, several studies have found opposite results as well. For example, Watanabe & Hirato (1985) found that the perceptual boundaries between singletons and geminates shift toward longer duration after longer vowels, although only two listeners participated in this study. A similar boundary shift was found in Hirata (1990). Idemaru & Guion-Anderson (2010) kept the duration of the consonant at about 140ms and changed the duration of the preceding mora (C_1+V_1), and found that the shorter the mora duration, the more geminate responses were obtained (though see Takeyasu 2012 who argues that it is the duration of C_1/V_1 ratio that matters, and that higher C_1/V_1 ratio would lead to more geminate percepts.). See Takeyasu (2012) for more references for studies that obtained the results in this direction.

In summary, some studies found an "assimilative" pattern (more geminate responses after longer vowels) while others found a "contrastive" pattern (more geminate responses after shorter vowels). It is an interesting question where the difference between the two types of results come from. There is some evidence that the magnitudes of the duration ratios between the target and context matters in this regard (Nakajima et al., 1992). Takeyasu (2012) also entertains a hypothesis that in experiments that obtained an contrastive effect, listeners may have judged the preceding vowels to be phonological long, in which case they are biased against judging the following consonant as long to avoid a superheavy syllable (see Kubozono 1999 for a phonological constraint against superheavy syllables in Japanese). Further experimentation is necessary to settle this issue.

Unlike preceding vowels, vowels are shorter after geminates than after singletons (Campbell, 1999; Han, 1994; Idemaru & Guion, 2008; Ofuka, 2003) (see section 2.2.1). While Hirato & Watanabe (1987) found no effects of the duration of the following vowel on the perception of geminates, Ofuka et al. (2005) did indeed find that listeners are more likely to judge the stimuli

as a geminate before a shorter vowel; Idemaru & Guion-Anderson (2010) found a similar effect, although they found the effect of preceding CV mora to be more substantial. See also Nakajima et al. (1992) for a relevant discussion.

Furthermore, Hirata (1990) tested the effect of sentence level speech rate on perception of length contrasts, and found that the durations of the whole sentential materials following the target word can impact the perception of geminates. The study found that those tokens that are unambiguously identified as either a singleton or a geminate can be perceived as a member of a different category if the following materials provide enough cues for speech rate.

One remaining question in this regard is, when listeners normalize the perceived duration for speech rate, to what extent they rely on local cues (like immediately preceding/following vowels or (CV) moras), and to what extent they rely on more global cues (like entire speech). On the one hand, in terms of psycholinguistic computational simplicity, local cues are presumably easier to track (Idemaru & Guion-Anderson, 2010); on the other hand, some studies (Amano & Hirata, 2010; Hirata, 1990; Pickett & Decker, 1960) show the effect of global cues; for example, by comparing several relational measures, Amano & Hirata (2010) demonstrates that the relationship between consonant duration and word duration[12] provides a good perceptual cue to a length distinction in Japanese.

However, taking into account a whole word or sentence to determine a length property of a single contrast may impose a psycholinguistic burden: in order to identify what the word is, it is necessary to determine whether the consonant in question is a singleton or a geminate. I do not wish to imply that this challenge is insurmountable, and more phonetic and psycholinguistic research is necessary to address this issue. In summary, the relationship between production and perception of geminates in Japanese (and other languages) provides an interesting forum of research, which may bear on the general theory of speech perception (see Amano & Hirata 2010; Idemaru & Guion-Anderson 2010; Otaki 2011; Pind 1986 and others for discussion).

Another remaining question is how non-durational cues—F0 values and movement, spectral envelope, burst intensity, etc (see also Table 2)—interact with durational cues in the perception of Japanese geminates. For example, Ofuka (2003) observes that geminates are shorter in accented disyllabic words than in corresponding unaccented words, and also that in perception shorter closure duration can yield geminate perception when the word is accented (see also Hirata 1990 who obtained similar results). Likewise, Kubozono et al. (2011) show that English monosyllabic utterances with a falling pitch contour is more likely to be perceived as geminates by Japanese listeners. More extensive studies are warranted to investigate the intricacy of perception of geminates in Japanese.

[12]They demonstrate that it is not a simple ratio between these two measures, but a regression function with an intercept that most accurately predicts the perceptual behavior of Japanese listeners. This function is equivalent to the ratio between closure duration plus some constant and word duration; i.e. $(C + k)/W$ (where k is a constant).

3.3 Comparison with other languages

Like Japanese, the effect of constriction duration on the perception of duration has been found in many languages; e.g. Arabic (Obrecht, 1965), Bengali (Hankamer et al., 1989), English[13] (Pickett & Decker, 1960), Hindi (Shrotriya et al., 1995), Italian (Esposito & Di Benedetto, 1999; Kingston et al., 2009), Norwegian (Kingston et al., 2009), Pattani Malay (Abramson, 1987a, 1992), and Turkish (Hankamer et al., 1989).

Across languages, the effect of language particular implementation pattern—shortening or lengthening of preceding vowel—is often reflected in the perception pattern as well. For example, both in Norwegian and Italian, vowels are shorter before geminates, unlike Japanese (Esposito & Di Benedetto, 1999; Fintoft, 1961). This shortening affects the perception of geminates—listeners of these languages perceive a consonant more likely as a geminate before a shorter vowel than a longer vowel (Esposito & Di Benedetto, 1999; Kingston et al., 2009; van Dommelen, 1999). In Icelandic in which long vowels and geminates are in a complementary distribution, Pind (1986) shows that vowel duration with respect to the entire rhyme duration is a good predictor for geminate perception—given fixed rhyme durations, shorter vowel durations yielded more geminate responses.

One interesting puzzle that arises from a cross-linguistic comparison regarding shortening vs. lengthening in pre-geminate position is as follows: some researchers proposed that C/V duration ratios provides mutually enhancing perceptual cues for duration when a shorter consonant is preceded by a longer vowel, as is the case for voicing contrasts in many languages (Kingston & Diehl, 1994; Kohler, 1979; Pickett et al., 1999; Port & Dalby, 1982). A combination of a short vowel and a long consonant yields enhanced, high C/V_1 duration ratios, whereas a combination of a long vowel and a short consonant yields low ratios. Languages like Italian and Norwegian, in which preceding vowels are shorter before geminates, can be assumed to deploy this perceptual enhancement pattern. In this light, a question arises why Japanese lengthens a vowel before a geminate. A tentative answer that I can offer is that V_1C unit (or V-to-V interval) may constitute a perceptual unit, a unit that has been hypothesized to play a role in the perception of Japanese and other languages (Hirata & Forbes, 2007; Kato et al., 2003; Kingston et al., 2009; Ofuka et al., 2005; Sato, 1978; van Dommelen, 1999).[14] If V_1C is an important perceptual unit—whether it is universal or specific to Japanese—then a longer vowel before a geminate can be considered as perceptually enhancing the long duration of geminates.

[13] English does not have a lexical geminate contrast; this experiment tested a pair like *topic* vs. *top pick* where one member of the pair contains multiple morphemes.

[14] An alternative idea is that although Japanese is a mora-timed language (where a mora usually constitutes a CV unit), geminates, whose coda part should constitute its own mora, are not by themselves as long as a CV unit; pre-geminate vowel lengthening may occur to compensate for this shortage of duration, as hypothesized and discussed by Warner & Arai (1999). See also the chapter on mora-timing. One puzzle for this explanation is why, then, Japanese speakers shorten the following vowels after geminates.

4 Articulatory studies of Japanese geminates

Compared to acoustic and perception studies of Japanese geminates, there are a relatively fewer studies on articulations of Japanese geminates, although there are some notable studies. Fujimura & Williams (2008), based on X-ray microbeam data of Ishii (1999), for example, show the prolonged articulation of a geminate [pp] in Japanese compared to a singleton [p]. Smith (1995) shows based on X-ray microbeam data that in Japanese a singleton/geminate distinction affects the gestural timing of the following vowel, whereas in Italian it does not. The study also found that the lips move more slowly for geminates than for singletons, and this tendency was found for both Japanese speakers and (some) Italian speakers. The same tendency was identified by Fujimura & Williams (2008) as well as by Takada (1985) for Japanese speakers. Takada (1985) found a slower movement for geminates in terms of lingual contact, in addition to jaw movement, in that maximal constriction is formed at the later phase of constriction. Sawashima (1968), using a fiberscope, shows that glottal abduction is larger for geminate fricatives than singleton fricatives. Finally, Kokuritsu-Kokugo-Kenkyuujo (1990) offers detailed articulatory data of Japanese sounds in general, including those of geminates.

5 Remaining issues

Although I have raised a number of remaining questions already, I would like to close this chapter with discussion of several more remaining issues that require further experimentation.

5.1 Non-intervocalic geminates

Although for lexical contrasts, Japanese allows geminates only intervocalically, some word-initial geminates are found due to an elision process in casual speech; e.g. [ttaku] from /mattaku/ (a phrase that often accompanies a sigh) and [sseena] from /usseena/ 'shut up'. Cues to word-initial geminates have been studied in some other languages (Abramson, 1992, 1999; Kraehenmann & Lahiri, 2008; Muller, 2001; Ridouane, 2010), but the Japanese case has not been extensively investigated. A specific question is whether such word-initial geminates involve longer constriction just like intervocalic geminates. Articulatory studies, using devices like EPG (Kraehenmann & Lahiri, 2008; Payne, 2006; Ridouane, 2010), would address this question of whether word-initial geminates do indeed involve longer constriction (Kraehenmann & Lahiri 2008 and Ridouane 2010 found a positive answer to this question in Swiss German and Beber).

Similarly, an orthographic marker for Japanese geminates—"small tsp" —can also appear word-finally, especially in mimetic words (see the chapter on mimetics). However, the exact nature

of its phonetic realization is also yet to be explored—it is likely that it is realized as a glottal stop, but as far as I know, it has not been fully explored. See the chapter on mimetics.

5.2 Derived geminates vs. underlying geminates

Some phonetic studies in other languages have compared lexical geminates and geminates derived by some phonological processes, most often by assimilation.[15] They have generally shown that lexical geminates and geminates derived via a phonological processes are phonetically identical, as in Berber (Ridouane, 2010), Bengali (Lahiri & Hankamer, 1988), Sardinian (Ladd & Scobbie, 2003), and Turkish (Lahiri & Hankamer, 1988). However, Ridouane (2010) found a difference between lexical geminates and geminates created via morpheme concatenation in terms of preceding vowel duration and burst amplitude. Similarly, Payne (2005) argues that in Italian lexical geminates tend to be longer than post-lexical geminates created by RADDOPPIAMENTO SINTATTICO (RS) (although there are some complicating factors; see Payne 2006 for further discussion.)

As far as I know no studies have compared underlying and derived geminates in Japanese. For example, the final consonant of a prefix /maQ-/ 'truly' assimilates to the root-initial consonant, resulting in a geminate (e.g. [mak-ka] 'truly red' and [mas-sakasama] 'truly reversed'). It would be interesting to investigate whether there remains a difference between such derived geminates and underlying geminates. One reason why we may expect a difference is as follows. Monomoraic roots in Japanese can be lengthened when pronounced in isolation without a particle (Mori, 2002); however, duration ratios between these lengthened vowels and short vowels are smaller than the ratios between underlying long vowels and short vowels found in the previous research (Beckman, 1982) (Mori 2002 did not record lexical long vowels, so direct comparison was not made). It would be particularly interesting if we find such an incomplete neutralization pattern (Port & O'Dell 1985 *et seq.*) in the context of gemination.

5.3 Phonetics of emphatic geminates

Japanese deploys gemination for emphasis (e.g. [sɯgːgoi] 'excellent' from [sɯgoi]). In terms of orthography, this gemination can be written with multiple signs of gemination ("small tsu") (Aizawa, 1985). It would be interesting to investigate to what extent such repetition of geminate diacritics is reflected in actual production (and for that matter, can be tracked in perception). This issue is addressed in a project by the author in progress.

[15] In some languages, geminates can arise via simple morpheme concatenation without a further phonological change (known as "fake geminates"); e.g. /pat̪+t̪e/ → [pat̪ːe] 'spread out (infinitive)' in Bengali (Lahiri & Hankamer, 1988)). In Japanese, fake geminates rarely if ever arise because root-final consonants always assimilate to the following consonant anyway.

Furthermore, this emphatic gemination pattern can create otherwise unacceptable types of geminates, such as voiced obstruent geminates in native words and approximant geminates (Aizawa, 1985; Kawahara, 2001). Together with the general phonetic properties of emphatic geminates, the phonetic realization of approximant geminates, in particular, has been understudied and is yet to be investigated.

5.4 Laryngeal "tension" of geminates

Despite the studies mentioned in section 4, the exact articulatory nature of Japanese geminacy contrasts is yet to be explored. One particular issue concerns whether Japanese geminates involve laryngeal constriction or not. Impressionistically, sometimes Japanese geminates are conceived of as accompanying glottal constriction. Hattori (1984) suggests that the first half of geminates involves glottal tension (p. 139). Idemaru & Guion (2008) also found shallower spectral tilt (H1-A1) in the vowels following geminates, indicating some creakiness, which implies some glottal constriction (although we should also note that two other measures of creakiness did not show differences in their study). Fujimura & Williams (2008) argue that laryngealization is a distinctive characteristics of Japanese geminates, which may even contribute to the perception of geminates. Whether Japanese geminates involve glottal articulation, and if so how that glottalization is coordinated/sycnrhonized with super-laryngeal (oral) gestures, is to be explored.

5.5 Dialectal differences

There are few cross-dialectal studies on Japanese geminates, especially those written in English, which would be available to those scholars who do not read the Japanese literature. Due to the limitation of my expertise, I cannot discuss this issue extensively, but it would be particularly interesting to compare the properties of geminates in mora-timed dialects and syllable-timed dialects (such as Aomori dialect) (Takada, 1985).

5.6 Manner differences and the perception of geminates

Finally, as discussed in section 2.3, manner effects on the production of geminates in Japanese have been understudied. Relatedly, many perception experiments on Japanese geminates are based on voiceless stops (Amano & Hirata, 2010; Arai & Kawagoe, 1998; Hirata, 1990; Hirato & Watanabe, 1987; Fukui, 1978; Idemaru & Guion-Anderson, 2010; Kingston et al., 2009; Ofuka, 2003; Takeyasu, 2012; Watanabe & Hirato, 1985). Fujisaki et al. (1975) studied all the manners, but nevertheless only report the results of fricatives. There are a few recent studies (Matusi, 2012; Takeyasu, 2009; Tews, 2008) which investigated factors affecting the perception of geminates in

fricatives. Oba et al. (2009) showed that the primary cue for affricate geminates lies in the closure phase, not in the frication phase. Further experimentation comparing the production and the perception of different manners of geminates, including nasal geminates, would warrant further studies.

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