Processing of Phonemic Consonant Length: Semantic and Fragment Priming Evidence from Bengali

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Abstract
Six cross-modal lexical decision tasks with priming probed listeners' processing of the geminate–singleton contrast in Bengali, where duration alone leads to phonemic contrast ([pata] 'leaf' vs. [patːa] 'whereabouts'), in order to investigate the phonological representation of consonantal duration in the lexicon. Four form-priming experiments (auditory fragment primes and visual targets) were designed to investigate listeners' sensitivity to segments of conflicting duration. Each prime derived from a real word ([kʰɔm]/[gʰenː]) was matched with a mispronunciation of the opposite duration (*[kʰɔmː]/*[gʰen]) and both were used to prime the full words [kʰɔma] ('forgiveness') and [gʰenːa] ('disgust') respectively. Although all fragments led to priming, the results showed an asymmetric pattern. The fragments of words with singletons mispronounced as geminates led to equal priming, while those with geminates mispronounced as singletons showed a difference. The priming effect of the real-word geminate fragment was significantly greater than that of its corresponding nonword singleton fragment. In two subsequent semantic priming tasks with full-word primes a stronger asymmetry was found: nonword geminates (*[kʰɔmːa]) primed semantically related words ([marjona] 'forgiveness') but singleton nonword primes (*[gʰena]) did not show priming. This overall asymmetry in the tolerance of geminate nonwords in place of singleton words is attributed to a representational mismatch and points towards a

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moraic representation of duration. While geminates require a mora which cannot be derived from singleton input, the additional information in geminate nonwords does not create a similar mismatch.

Introduction

The human brain's processing system expertly handles durational cues, which are essential not only for performing tasks such as those involving hand-eye coordination and locomotion, but also for language production and processing. In language, time is relevant not only with regard to variables such as speech rate but also on the level of individual phonemes which contrast only in their duration (e.g., in Bengali[1] [kana] 'deaf' vs. [kanːa] 'tears'). The focus of this paper is on the processing and representation of such durational contrasts. Previous research has shown human listeners to be sensitive to durational differences as small as 12.5 ms (cf. Näätänen, Paavilainen & Reinikainen, 1989), but there is little work on how these durational differences affect lexical access in languages which use duration to discriminate meaning. The present research aims to examine the suitability of different representational possibilities for the contrast between long and short consonants, using lexical decision tasks with priming to determine how duration is represented in the lexicon.

Every model of speech perception, which necessarily includes hypotheses concerning phonological representations, has to be able to account for the considerable variation in the acoustic signal which results from the many factors affecting the realization of spoken words (e.g., speaker variation, noisy environments, speech rate). The question of how much and what kind of variability can be tolerated in the speech signal while still leading to accurate processing has been the subject of intensive debate in the last two decades. The majority of studies have concentrated on the variability in the featural information of segments: for example, place or manner of articulation (Cornell, Lahiri & Eulitz, 2011, 2013; Friedrich, Lahiri & Eulitz, 2008; Gaskell & Marslen-Wilson, 1999, 2001, 2002; Lahiri & Marslen-Wilson, 1991; Pitt, 2009; Ranbom & Connine, 2007). However, none of these models provide an explicit account of how duration is processed during speech perception and how it may be represented in the lexicon.

This paper focuses on the nature of phonological representation of lexical duration in Bengali and how these representations can be determined by investigating the processing of the geminate–singleton contrast. The central question is how durational information is stored in the lexicon and thus how manipulations in duration affect the recognition of a word. To what extent do mispronunciations resulting from incorrect duration hinder lexical access and recognition even though all other segments and features in the word remain constant? What does this reveal about the representation of durational information in the lexicon? Would duration contrasts result in processing asymmetries like those observed for featural contrasts (see, among others, Bölte & Coenen, 2000; Eulitz & Lahiri, 2004; Roberts, Wetterlin & Lahiri, 2013)? From earlier studies on Bengali, we know that exchanging the closure duration of medial consonants in minimal pairs is enough to change perception—that is, switching the closure duration of the nasal in [kanːa] 'tears' and [kana] 'blind' reversed the perception of these words (Hankamer, Lahiri & Koreman, 1989). However, if replacing the duration of closure leads to a nonword, would listeners still be able to access the corresponding real word? In other words, if [patʰor] 'stone' or [dana] 'seed/grain' are produced with a long [tʰː] or [nː] giving the mispronunciations *[patʰːor] and *[danːa][2] would

listeners ignore the excess durational information and still activate the intended word? Similarly, would *[gʰena] and *[dokʰin] be accepted as variants of the real words [gʰenːa] 'disgust' and [dokʰːin] 'west', respectively? That is, would the featural information alone be enough for recognition despite the incorrect durational information? Furthermore, an N400 study (lexical decision tasks with semantic priming; Roberts, Kotzor, Wetterlin & Lahiri, 2014) has shown asymmetric processing of geminate and singleton mispronunciations, where a singleton could be replaced by a geminate without this affecting lexical access while the reverse was not possible. The behavioural data from this study, however, was not conclusive. The present study uses behavioural lexical decision tasks with both form and semantic priming to more thoroughly probe this asymmetry and its consequences for the lexical representation of duration.

1.1 Consonant duration

Languages with an underlying contrast in consonantal length typically have a binary distinction between short (singleton) and long (geminate) consonants (Phillips et al., 2000; Raizada & Poldrack, 2007; Reetz & Jongman, 2009; Sharma & Dorman, 1999).[3] Across the world's languages, most types of consonants (stops, nasals, affricates, etc.) can occur as geminates, and geminates are attested in initial, medial and word-final positions (Davis, 1999; Müller, 2001). Duration contrasts manifest either in the duration of the silent closure (voiceless plosives, [pː]-[p]) or that of the voicing of sonorants (nasals, liquids, e.g., [nː]-[n]) or obstruents (voiced plosives, e.g., [dː]-[d]). Despite being a fundamentally gradable property, duration has frequently been shown to be perceived categorically, that is, heard as being either long or short, for both voice onset time and consonantal duration (Hankamer et al., 1989; Kuhl & Miller, 1978; Phillips et al., 2000). The duration of consonants may be enhanced by additional release properties such as differences in pitch or aspiration (Pattani Malay (Abramson, 1986, 1987, 1999) or Cypriot Greek (Müller, 2001; Ridouane, 2010 and references therein)). Furthermore, vowel and consonant duration sometimes exist in complementary distribution, as in stressed syllables in Norwegian (Kristofferson, 2000), Swedish (Riad, 2014) and Italian (Payne, 2006), where medial geminates are always preceded by stressed short vowels and singletons by long vowels, for example, Italian [ˈpapːa] 'purée' vs. [ˈpaːpa] 'pope', [ˈpaːla] 'shovel' vs. [ˈpalːa] 'ball' or Norwegian [ˈnisːe] 'imp' and [ˈniːse] 'porpoise'. Often languages differ with regard to specific additional acoustic cues, but longer consonant duration is a prerequisite for the identification of geminates, just as vowel duration is the most obvious acoustic manifestation separating long vowels from their short counterparts.

1.1.1 Representation of consonantal duration. Underlying medial geminate consonants, like those examined in this study, are usually treated as phonologically heterosyllabic (but see Topintzi, 2008 for a discussion of medial onset geminates) such that they belong to the coda of one syllable and the onset of the following syllable. The singleton medial consonant will always be only the onset of the second syllable. Therefore, the syllable structure of a word with a medial singleton will always differ from that of a word with a medial geminate. The Bengali examples in (1) illustrate the structural difference between medial singletons and geminates.

(1)   σ   σ   σ   σ

   p a t   a   p a t: a

   (a) [pata] 'leaf'   (b) [patːa] 'whereabouts'

Concerning the lexical phonological representation of this durational contrast, early generative grammars vacillated between (i) a feature distinction (where geminates were marked as [+LONG] and singletons were [-LONG]; Chomsky & Halle 1968) and (ii) a 'geminate notation' (Kenstowicz & Kisseberth, 1979: 377), where geminates were represented as a sequence of two identical segments (e.g., [tt] vs. [t]). These representations are illustrated in (2) below.

(2a) [±LONG] representation of underlying geminates

p a **t** a   p a **tː** a
        | |
   [-LONG]   **[+LONG]**

(2b) Representation of underlying geminates as a sequence of identical consonants

p a **t** a   p a **tt** a

In the late sixties and early seventies, syllable structure was not considered to be relevant and therefore syllabic divisions of geminates were not an issue. However, in a number of influential papers, Kenstowicz and Pyle (Kenstowicz, 1970; Kenstowicz & Pyle, 1973; Pyle, 1971, among others) argued that both [±LONG] and a geminate notation (e.g., [tt]) were necessary to account for the variety of phonological patterns observed across the languages of the world. For instance, the notation [tt] necessarily also captures sequences of identical [t]s at morpheme boundaries; for example, Bengali *pat-t-o > patto* 'lay-3person-past'. Nevertheless, a real geminate in a word like [patːa] 'whereabouts' needs to be distinguished from a sequence across morphological boundaries such as that seen in *patto*. For the latter, it is possible to separate the resulting geminate by vowel epenthesis in the formal variety of Bengali (which was also the vernacular in the 18th century), giving [patito], while the underlying geminate in [pat ːa] cannot be separated. Here a feature contrast [+LONG] would help so that the underlying geminate [+LONG] consonant /tː/ would block epenthesis, while the [-LONG] [-LONG] [tt] sequence would not. More evidence from various languages shows that whereas underlying (lexical) geminates cannot be broken up by epenthetic vowels, geminates arising from concatenation can be separated (e.g., compare i-insertion in Palestinian Arabic *fut-t* 'enter1Sg' > *fut-i-t* 'enterPast1Sg' to its absence in *sitt-na* (*sitit-na*) 'our grandmother'; Abu-Salim, 1980).

Consequently, Kenstowicz and Pyle (1973: 42) introduced the term 'geminate integrity' and argued that, "all other things being equal, rules of metathesis, copying, epenthesis—rules which break up clusters—are blocked from applying if their application would result in the separation of a geminate cluster from its twin". Nevertheless, the combined [-LONG][-LONG] sequence [tt] in [pat-t-o], which allows epenthesis, is also a geminate on the surface and is acoustically no different from the one in [patːa].[4]

Thus, geminates are required to be a single unit on one level, while being a sequence of two on another level. When autosegmental hierarchical representations became accepted for tonal languages, suggesting that a single tone can be multiply linked to a number of vowels (e.g., Leben, 1980), and non-concatenative morphology also proved to require hierarchical templatic structures giving multiple surface outputs from single consonantal roots in Semitic languages (McCarthy, 1982), it became easier to combine the two types of representations for geminates. Even then, however, there were two competing views on the structural representations of geminates—a skeletal representation giving timing units versus a moraic representation where geminates are automatically assumed to carry weight (e.g., Hyman, 1985). The different conflicting representations of singleton and geminate phonemes (including syllable structures) are given in Figure 1. Note that in both instances, the medial geminate is treated as heterosyllabic.
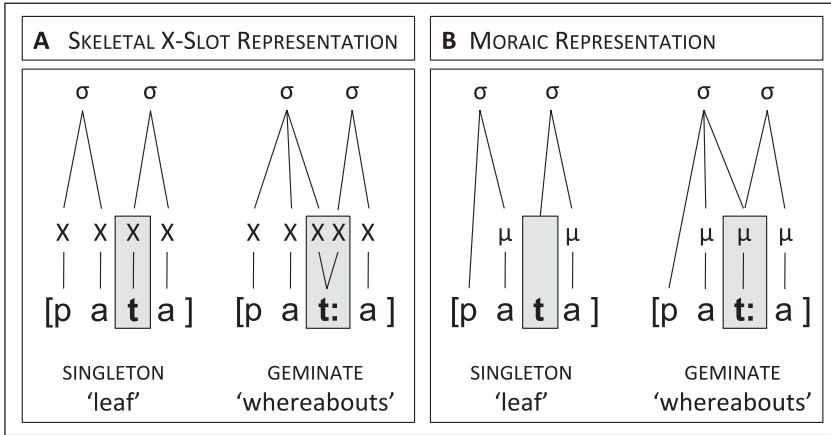
Figure 1. Skeletal X-slot representation and moraic representation with syllable structures.

The skeletal approach does not make any commitment that a geminate consonant automatically contributes to weight. The moraic representation, however, strongly supported by Hayes (1989), inherently assumes that a medial geminate carries a mora which aligns itself to the coda of the preceding syllable thereby making the initial syllable heavy (see Figure 1(b)). A shortened consonant cluster or degeminated medial geminate would leave a mora free and this would then be filled by lengthening a preceding vowel—a process which is known as compensatory lengthening. This makes perfect sense in a moraic theory, but would need further explanation in an X-slot skeletal representation.

Nevertheless, there have been several arguments against moraic representations of geminates (see Davis, 2011 for summary). One source of argument is that a moraic representation makes false claims about initial geminates, which ordinarily should not carry weight (see Kraehenmann, 2011 for Swiss German). Another argument against the moraic representation is that even medial geminates need not necessarily make a syllable heavy (Mohanan and Mohanan, 1984). In Malayalam, for instance, only long vowels contribute to syllable weight, although the language is replete with geminates, whether underlying, concatenated or occurring by assimilation; no syllable closed by a geminate is heavy with respect to stress. Consequently a moraic representation of length would be misleading, at least for Malayalam.[5]

Bengali does not provide data which would allow us to differentiate between different representations of duration on a structural level, that is, between skeletal, moraic or dual representations. The question we are asking here is whether duration is indeed represented on a structural level or whether it is a featural contrast, as there is little evidence to choose between these two fundamentally different approaches. Synchronic Bengali phonological analyses can be handled by either a [±LONG] feature contrast or any structural hierarchical contrast. There is no evidence from metathesis, epenthesis, syllabification, or indeed stress to suggest that a hierarchical representation is necessary. The issue we raise is whether processing differences shed light on the nature of the representation of this contrast, since the two approaches (structural versus featural) introduced above will have different consequences for processing. For the sake of simplicity, when we present our hypotheses, we compare only one of the structural representations with the featural representation. Since the Bengali phonological system does not choose between dual, skeletal, and moraic representations, we have opted for the third option since for other purposes, like metrical stress and reduplication, moraic feet are well established in phonological analyses of the languages of the world. When discussing the results, we will return to the skeletal versus moraic representational hypotheses.

1.1.2 Geminates in Bengali. Bengali has 25 consonants, 23 of which contrast in length word-medially irrespective of manner or place of articulation (Hankamer et al., 1989; Lahiri & Hankamer, 1988).[6] In previous studies, it has been shown that the average geminate in Bengali is approximately twice as long as the average singleton. Neither preceding vowel duration nor any release properties consistently distinguish geminates from their singleton counterparts (Hankamer et al., 1989).

In Bengali, as in some other languages, for example Turkish, closure duration overrides other cues for length contrasts in the signal when measured in naturally occurring geminates or singletons (Lahiri & Hankamer, 1988: 285; see also Hankamer et al., 1989; Lahiri & Marslen-Wilson, 1992; Ridouane, 2010). These studies found that when the closure duration was cross-spliced between geminate and singleton minimal pairs, keeping all other cues constant, listeners' perceptions switched accordingly. Consequently, a word like [kana] 'blind' artificially supplied with a long closure duration was heard as [kanːa] 'tears' and vice versa (Hankamer et al., 1989). These results further attest to the perceptual salience of closure duration over other cues involved in geminate/singleton discrimination in Bengali.

1.2 Previous research on geminate perception and processing

Geminates have been studied extensively in terms of their phonetic and phonological properties as well as their perception (see among others Catford, 1977; Davis 2011; Hayes, 1986, 1989; Kingston, Kawahara, Chambless, Mash & Brenner-Alsop, 2009; Lisker, 1958; Payne, 2005; Perlmutter, 1995; Ridouane, 2010 and references therein; Schein & Steriade, 1986). There is, however, a scarcity of research on the processing of consonantal duration. There are a small number of studies (most notably Lahiri & Marslen-Wilson, 1992; Tagliapietra & McQueen, 2010) and of those, the gating study by Lahiri and Marslen-Wilson (1992), which examines duration contrasts in Bengali, provides a useful reference point for the experimental investigation of geminate processing and representation.

Lahiri and Marslen-Wilson (1992: 250) suggest that the interpretation of consonant duration in the speech signal does not depend on the lexical status of a feature (unlike place features or nasality) but "on the listener's assessment of the segment slots and therefore of the prosodic structure." They used disyllabic minimal pairs with medial sonorants (e.g., [kana] 'blind' ~ [kanːa] 'tears'), which were presented in fragments (i.e., 'gates') of incrementally increasing duration. Listeners were required to respond by writing down the full word they thought would represent the correct continuation of the fragment. Two fragments were crucial: the first (gate 3), which included the entire closure duration of the medial consonant but not the release, and the second (gate 4), which included the release (approximately 15 ms). The entire closure duration (average geminate duration: 190 ms; average singleton duration: 80 ms), although acoustically clearly distinct, was not sufficient to distinguish between geminates and singletons. When hearing the complete closure duration of [kanːa], only 20% of the listeners' responses contained geminates. Even with the addition of the release (gate 4), the stimuli remained ambiguous and geminate responses accounted for only about 55% of the total. The authors conclude that a geminate cannot be interpreted correctly until both the structural and featural information is available, because geminates and singleton medial consonants result in different syllable structures and this information is required to accurately determine whether the consonant in question is a geminate or singleton. Lahiri and Marslen-Wilson's data (1992) shows that singletons are often proposed in place of geminates even when the full closure duration, which is considerably longer than that of a singleton, is available to the listener. This shows a disproportionately large degree of acceptance of the singleton when the fragment in question was taken from a geminate.

The findings of this gating study (Lahiri & Marslen-Wilson, 1992), which show an asymmetry in an offline task, combined with the fact that synchronic observation of Bengali data does not provide us with any evidence which would allow for a distinction between the two representational possibilities introduced above, suggest that further experimental investigation of the duration contrast in Bengali is warranted.

1.3 The present study

Using listeners' reactions to mispronunciations of consonant duration will allow us to investigate the details of the phonological representations of the geminate-singleton contrast. Since mispronunciation tasks (with featural contrasts) have been used successfully with both adults and children to determine the restrictions on the amount of variation tolerated before lexical access is no longer achieved (among others Bailey & Plunkett, 2002; Bölte & Coenen, 2000; Mani & Plunkett, 2010; Roberts et al., 2013), we will use this method to examine duration. To investigate the effect of duration differences on lexical access, we use cross-modal lexical decision tasks with both form priming (Experiments 1–4) and semantic priming (Experiments 5 and 6), making use of mispronounced medial geminates and singletons. All mispronunciations were created by shortening or lengthening the duration of the medial consonant of the corresponding real word.

Previous work on listeners' acceptance of mispronunciations and the extent to which these result in lexical access broadly covers two aspects: change in segmental features, such as place or voicing (*gree[m] for gree[n], or *fa[d]el for fa[b]el, *[p]ag for [b]ag etc.; see Bölte & Coenen, 2000; Gaskell & Marslen-Wilson, 1997; Lahiri & Reetz, 2002) and deletion and reduction of consonants (*coun[_]er for coun[t]er; e.g., Pitt, 2009). Experimental evidence and explanations accounting for the amount of variability tolerated in perception have given rise to extensive and controversial discussion.

Representational models accounting for variability propose a range of different theories involving the use of detailed acoustic information (Gow, 2003), full specification of word representations (Johnson, 1997; Pierrehumbert, 2001, 2002; Ranbom & Connine, 2007), contextual inference (Gaskell & Marslen-Wilson, 2001, 2002), auditory neutralization (Hura, Lindblom & Diehl, 1992; Mitterer, Csépe & Blomert, 2006) and abstract underspecified representations (Roberts et al., 2013; Wheeldon & Waksler, 2004; Zimmerer, Scharinger & Reetz, 2011). Despite diverging conclusions, the evidence suggests that certain types of mispronunciations are tolerated more easily than others due to differences in the specificity of their representations (e.g., Bölte & Coenen, 2000, 2002; Lahiri, 2012; Lahiri & Reetz, 2002, 2010; Roberts et al., 2013; Zimmerer et al., 2011), although studies of mispronunciations caused by non-featural contrasts such as duration or tonal differences are still quite rare.

Priming is based on the successful facilitation of the activation of a target's lexical representation through the use of a prime which is related to the target either semantically (e.g., gold-SILVER; river-STREAM), associatively (sand-BEACH; stripe-TIGER) or through its form (walking-WALK; places-PLACE; see Forster, 1999 and references therein). Cross-modal form priming with fragments has been used in a large number of studies and has shown that word onset fragments can activate the words they were extracted from, for example, in German [dra] primes Drache 'dragon' (Friedrich et al., 2008; Marslen-Wilson, 1990; Schütz, Schendzielarz, Zwitserlood & Vorbert, 2007; Zwitserlood, 1996). Semantic priming, where a semantically related prime–target combination has proven to lead to a faster response to the target in lexical decision tasks, is an established method for investigating not only the structure of the mental lexicon and how words are represented therein but also how they are accessed (Bölte & Coenen, 2000, 2002; Drews, 1996; Meyer & Schwaneveldt, 1971; Moss, Ostrin, Tyler & Marslen-Wilson, 1995; Scharinger & Lahiri, 2010). Our line of reasoning is as follows: if a
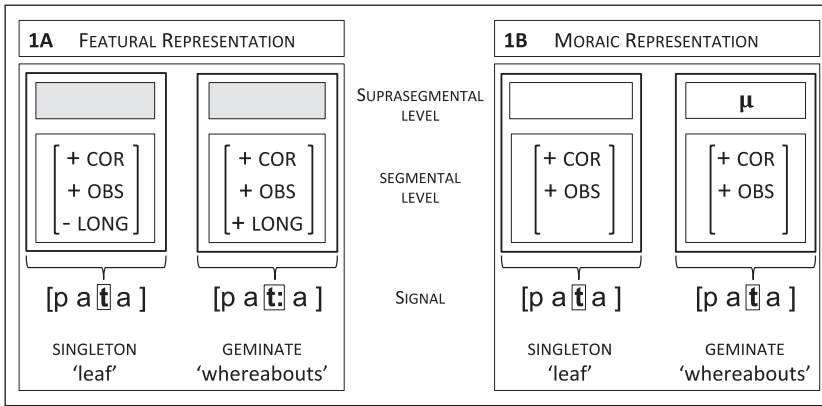
Figure 2. Segmental and moraic representations of consonant duration.

mispronounced word is accepted as a variant of an existing word, both the form and meaning of the real word should be accessed, thus leading to the pre-activation of the real word's semantic cohort. Consequently, a semantically related target following the mispronounced variant would result in faster recognition latencies. If the mispronunciation is rejected as a word, pre-activation of semantic associates does not occur and no semantic relationship is established, thus leading to reaction times similar to those of an unrelated control item.

1.4 Predictions

Here we briefly introduce the broad outline of our predictions, while the separate predictions of the form priming and semantic priming tasks will be discussed in more detail with the individual experiments. If we assume that the singleton and geminate consonants are distinguished by [+LONG] or [-LONG], then as soon as the listener identifies the appropriate length, the relevant phoneme is activated and the representation in the lexicon will contain [+LONG] for geminates and [-LONG] for singletons. Thus processing patterns observed in the data should be symmetric. If, however, the representation is based on structural differences, we predict an asymmetry in processing terms. A short consonant is unspecified for a moraic representation while the geminate is specified by a mora (see Figure 2). Featural information (nasal vs. obstruent, labial vs. coronal) becomes available early in the signal (Warren & Marslen-Wilson 1987, 1988), while differing durational information will not immediately start to affect lexical choice since the duration of the medial consonant remains to be ascertained. If a mispronounced geminate version *[ʃonːa] of the real word [ʃona] ('gold') is perceived, then the listener will still activate the real word because the full geminate consonant does not mismatch with an unspecified singleton. The opposite, however, does not hold. A mispronounced version (*[gʰena]) of the real word [gʰenːa] ('disgust') is a mismatch; although the coronal nasal features are the same, the representational information of [gʰenːa] has a mora which is not activated by the singleton [n] of the mispronounced word.

　Our predictions fall in line with the no-mismatch and mismatch predictions of the Featurally Underspecified Lexicon (FUL) (Lahiri & Reetz, 2002, 2010), where a perfect match of features is not necessarily required for listeners to activate a real word when hearing a mispronounced word. Consequently, the [m] of the nonword *sommet* in English activated the unspecified [n] in *sonnet*, but the [n] of *inage* did not activate the specified labial [m] in *image* (Roberts et al., 2013). The main thrust of our hypotheses is that if the Bengali geminate–singleton contrast is differentiated on
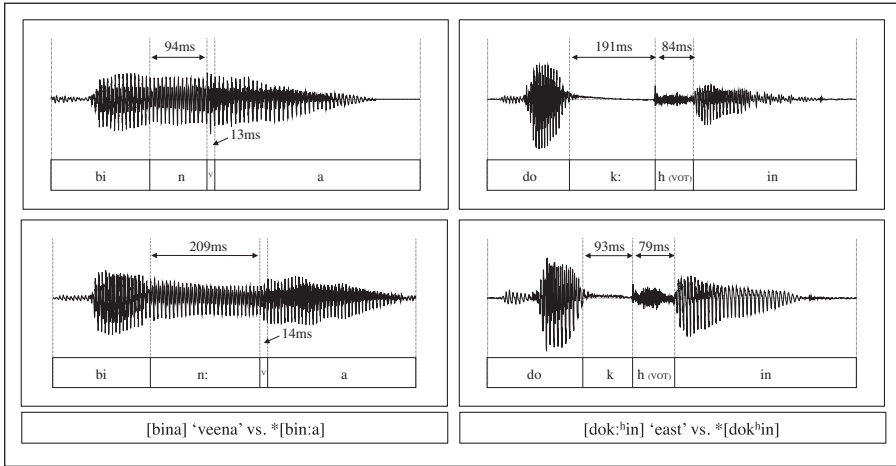
Figure 3. Comparison of a real-word geminate and singleton and their mispronunciations with the end of both CVC and CVC_v fragments marked.

the basis of a structural moraic representation, we would expect an asymmetry in the experimental tasks. If the representation is purely on the basis of [±LONG] then we would expect complete identity match and hence no asymmetry.

2 Fragment priming experiments (Experiments 1–4)

In this study we conducted four form-priming experiments with two different types of fragments: CVC and CVC_v. CVC fragments include the complete duration of the medial consonant while CVC_v fragments include an additional two glottal pulses (an average of 16 ms) of the following vowel to ensure that the syllable structure of the fragment is unambiguous. Furthermore, the length of these fragments in the form-priming tasks corresponds to the critical gates in the gating study introduced above (Lahiri & Marslen-Wilson, 1992). Tag 2 corresponds to gate 3 and the final tag (Tag 3) is identical to gate 4. Figure 3 displays examples of two test words and their mispronunciations. The first tag placed on the waveforms marks the offset of the first vowel. The second and third tags mark the end of the fragments used in Experiments 1–4 (CVC and CVC_v).

In Experiments 1 and 2 primes were CVC fragments including the entire duration of closure and release, while in Experiments 3 and 4 the fragment primes consisted of the same CVC fragment plus approximately 16 ms of the following vowel (CVC_v). The question is whether there is a difference between shorter and longer mispronounced fragments or whether they result in similar (symmetric or asymmetric) patterns of priming.

In Experiments 1 and 3 (SHORT > *LONG), fragments of real singleton words ([kʰɔma] 'forgiveness') and their geminate mispronunciations (*[kʰɔmːa]) are used as auditory primes for the full-word visual targets ([kʰɔma] ক্ষমা 'forgiveness'). Experiments 2 and 4 (LONG > *SHORT) uses the reverse; real-word prime fragments contain medial geminates (e.g., [bigːæn] 'science') which are shortened to singletons (*[bigæn]) in the mispronunciation condition (Target: [bigːæn] বিজ্ঞান 'science'). These four experiments were used to establish whether the mispronunciations would still result in priming and whether online tasks would result in an asymmetric pattern of processing and allow for conclusions to be drawn concerning the representation of durational contrasts.

2.1 Fragment form-priming predictions

The phonological representations introduced above predict different patterns of results. If the contrast is represented by a binary feature, it would be logical to assume that the opposing polarity of the feature in mispronunciations would cause a mismatch in either direction. Furthermore, if the [+/-LONG] phonological contrast is directly interpretable from the acoustic information, hearing the entire closure duration of the consonant should be sufficient to distinguish between geminate and singleton. This interpretation should thus lead to similar results in the CVC and CVC$_v$ experiments. However, if the difference between geminates and singletons does not lie in the segmental but in the suprasegmental information, we would expect an asymmetric activation pattern due to an asymmetric representation of duration where only the geminates are specified for length. In addition to the asymmetry, we may see a difference between Experiments 1 and 2 on the one hand and 3 and 4 on the other, since the fragment primes in the latter include more acoustic information (two glottal pulses of the following vowel), which may lead to faster processing since the duration of the consonant, and therefore its syllable structure, is now unambiguous.

As these four experiments use a form-priming paradigm, featural information may play a predominant role here since these tasks rely more heavily on the matching of form. This focus on features is further enhanced by the fact that the primes are fragments and segmental information is expected to play an important part in the matching process since it is available early on and is unambiguous. The structural information is not available until the duration of the medial consonant is clearly identified, and there will thus be less reliance on this type of information. Therefore, due to the large segmental overlap between even the mispronounced fragment prime and the target, we expect to see some priming with the mispronounced fragments in both directions. However, if our structural prediction proves to be correct, we may find an asymmetry in the degree of priming between the mispronounced singletons and mispronounced geminates which would point towards an asymmetric representation.

We furthermore expect slower reaction times in Experiments 1 and 2 since no vowel information is present, which may prevent listeners from making an accurate assessment of the prosodic structure of the fragment ([CV.C] vs. [CVC.C]). The longer fragments (CVC$_v$), which include some vowel information, should lead to a more accurate assessment of the duration of the medial consonant and therefore the structural properties of the whole word.

2.2 Method and materials

2.2.1 Participants. Fifty-six female native speakers of Bengali (aged 18–23; mean average age 19.67), all undergraduate students at Gokhale Memorial Girls' College (Kolkata), took part in the experiments. All participants had corrected-to-normal vision and no hearing (or other) impairments. The participants were compensated appropriately for their participation.

2.2.2 Primes. All prime words were disyllabic monomorphemic Bengali words with initial stress containing a medial (singleton or geminate) consonant. The mispronounced primes were created by replacing the medial singleton consonants with geminates (Experiments 1 & 3 (SHORT > *LONG): ([kʰɔma] 'forgiveness' to *[kʰɔmːa]) or the medial geminate consonants with singletons (Experiments 2 & 4 (LONG > *SHORT): [bigːæn] 'science' to *[bigæn]). All geminate and singleton primes (real words and their mispronunciations) were recorded by a female native speaker of Bengali. All primes were recorded as full words, rather than cross-splicing the medial consonant from one to the other or shortening or lengthening the medial consonant artificially, to ensure the stimuli were kept as natural as possible. The only manipulation performed on the recorded stimuli was to normalize them for amplitude differences. Words and nonwords were judged for authenticity by a Bengali native speaker. The full words were then truncated in PRAAT (Boersma & Weenink, 2011) to

Table 1. Prime–target combinations and predictions for Experiments 1–4.

***Form priming**: Experiments 1 (cvc) & 3 (cvc_v) -* SHORT > *LONG

Condition		Prime		Target	Competing Hypotheses	
		Ex 3: cvc	Ex 5: cvc_v		Symmetric	Asymmetric
Singleton (word)	related	**[kʰɔm]**	**[kʰɔm_v]**	ক্ষমা	√	√
	control	[dʒal]	[dʒal_v]	[khɔma] 'forgiveness'		
Geminate (nonword)	related	***[kʰɔmː]**	***[kʰɔmː_v]**		**X**	√
	control	*[dʒalː]	*[dʒalː_v]			

***Form priming**: Experiment 2 (cvc) & 4 (cvc_v) -* LONG > *SHORT

Condition		Prime		Target	Competing Hypotheses	
		Ex 4: cvc	Ex 6: cvc_v		Symmetric	Asymmetric
Geminate (word)	related	**[bigː]**	**[bigː_v]**	বিজ্ঞান	√	√
	control	[manː]	[manː_v]	[bigːæn] 'science'		
Singleton (nonword)	related	***[big]**	***[big_v]**		X	X
	control	*[man]	*[man_v]			

produce fragments of two different lengths. In Experiment 1 and 3, the primes consisted of the initial cvc fragments taken from each target word and its mispronunciation. The cvc fragments included the full consonant duration and the release ([kʰɔm]/*[kʰɔmː] with [kʰɔma] as target) whereas in Experiments 2 and 4 the first two glottal pulses of the following vowel were also included (cvc_v; [kʰɔm_v] /*[kʰɔmː_v]). The full-word mispronunciations were all possible words with regard to Bengali phonotactics. The test words were selected such that there was at most one word competitor after the crucial medial consonant, and no competitor with a medial consonant of the opposite duration. That is, for the word [bigːæn], no word which begins with the medial singleton fragment *[big-] exists, and there was at most one other word in the cohort of [bigː-] (e.g. [bigːo] 'learned'). The unrelated control primes were neither semantically nor phonologically related to the targets and their mispronunciations were constructed in the same way as those for the test primes (e.g., [dʒala] 'burn' > *[dʒalːa]). The primes and their targets were common words of Bengali (cf. Table 1 for example stimuli).

The average difference in duration between the cvc and cvc_v segments in the test and control conditions was 16.5 ms. In Experiments 1 and 3, the test condition primes consisted of 24 fragments taken from singleton words and their corresponding geminate mispronunciations as well as their control pairs. In Experiments 2 and 4, the fragments of 24 geminate primes were used alongside their mispronunciations and controls. In addition in all experiments, 48 filler primes and their mispronounced counterparts were also cut to cvc and cvc_v segments and used as primes for the 24 nonword targets.

2.2.3 Targets. The word targets were the matching words from which the fragment primes were taken (e.g., primes: [dʒʰin]/*[dʒʰinː] from target: [dʒʰinuk]). No words were used where the cvc auditory fragment was a word in its own right. Furthermore, all vowels in Bengali monosyllables are long. The vowels in the fragments, since they were extracted from disyllabic words, were considerably shorter and thus the fragments could not be mistaken for monosyllables (Fitzpatrick-Cole, 1996). All nonword targets were phonotactically possible words in Bengali. Each subject was presented with the 24 word targets, and 24 nonword targets paired with filler primes. All control primes were matched to the test primes as closely as possible. Since there are no frequency, familiarity or relatedness norms

Table 2. Frequency and familiarity rating task results.

	Frequency Rating (1–7)			Familiarity Rating (1–5)		
	T primes	C Primes	Targets	T primes	C Primes	Targets
Ex 1	6.56	6.70	6.61	5	4.992	5
Ex 2	6.77	6.81	6.35	5	4.997	5

for Bengali, we conducted three separate rating tasks to ensure appropriate frequency matching for test and control items as well as accurate degrees of semantic relatedness between primes and targets (cf. 2.2.5 & 3.2.5). Judgments of this type have been shown to correlate well with objective measures of frequency (see for example Segui, Mehler, Frauenfelder & Morton, 1982).

2.2.4 Stimulus recording. All primes—both real words and mispronunciations—were recorded by a female native speaker of Bengali in a sound-attenuated room with a Roland R-26 WAV recorder at a sampling rate of 44.1 kHz using a high-quality microphone (Shure SM27). The words were extracted, digitized and the volume equalized using the acoustic analysis programs PRAAT (Boersma & Weenink, 2011) and Audacity (Audacity Team, 2010). The average duration of geminates was 212 ms compared with an average duration of 99 ms for singleton primes (average difference: 113 ms; nasals: 122 ms; obstruents: 110 ms). There was no overlap between the geminate and singleton durations, with singletons ranging from 59 ms to 120 ms and geminates from 157 ms to 266 ms. The 100 ms difference between geminates and singletons is well attested for Bengali (Hankamer et al., 1989; Lahiri & Hankamer, 1988; Ridouane, 2010). The average duration of the preceding CV syllable was 210 ms in the case of the singletons and 207 ms for geminates.

2.2.5 Frequency and familiarity ratings. According to a study by Balota, Pilotti and Cortese (2001), subjective frequency estimates collected with the scale introduced below closely resemble word frequency scores extracted from corpora, and should thus be reliable. All questionnaires discussed below were completed by native speakers of Bengali.

In the *frequency rating* tasks, participants were asked to rate the frequency with which they encountered a word on a scale from 1 (never) to 7 (several times a day). All test and control primes as well as targets were included in the frequency rating (213 items in total). Due to the relatively large number of items, the words were randomly assigned to two different questionnaires (15 participants per questionnaire) to prevent participants from making random choices due to fatigue. Overall, there was a large degree of agreement between participants and the results of the frequency rating task are displayed below. Test and control primes were matched for frequency and only items with an average rating above five were included in the study.

The familiarity rating tasks were designed in the same manner as the frequency rating tasks but on a 5-point scale ranging from unfamiliar (1) to very familiar (5). All items were rated as very familiar (15 participants per questionnaire) and therefore no stimuli needed to be excluded on the basis of this rating task (results in Table 2).

2.2.6 Procedure. The experiments were conducted at Gokhale Memorial Girls' College in Kolkata, India. The participants were tested in groups of a maximum of 16 in a quiet and darkened room. The auditory primes were played through individual closed-ear headphones (SONY MDR110 LP) and visual targets were presented from a MacBook Pro in Bengali script and were projected onto one large screen. Subjects made their responses about the lexical status of the target word via custom-made individual two-button boxes with the buttons labeled in Bengali with 'yes' and 'no'. Subjects

used their dominant thumb for the 'yes' response and the other thumb for 'no'. After the subjects were instructed about the task, a practice session was run to ensure all participants had understood the task correctly. All subjects participated in all four experiments which lasted four minutes each. The experiments were separated and were run first and last, respectively, in a series of unrelated linguistic tasks to allow as much time between them as possible. The two CVC fragment experiments (1 & 2) were run first with the CVC$_v$ fragment experiments (3 & 4) run at the end of the experimental session.

A Latin Square design was used, which resulted in four blocks per experiment, to ensure every participant only saw each prime and target once but to allow for all four possible prime–target combinations across blocks. Targets were displayed for 1000 ms with an ISI of 0 ms from the offset of the auditory prime, and the interval between trials was 1500 ms. Subjects heard a beep before each prime (200 ms) and a sequence of two beeps after every 12 trials. The stimuli were presented with experimental software by Reetz and Kleinmann (2008). Trials were pseudo-randomized and presented in a different order in every block.

2.2.7 Methods for analysis. The reaction times of correct trials in all experiments (form and semantic priming) were analyzed with the statistics software JMP (SAS, 2012) using a linear mixed model for the fixed effects *relatedness* (related/control) and *wordness* (word/nonword prime) with subjects and items included in the model as random effects. Both random intercepts and random slopes were used and the data was checked for multicollinearity and linear distribution of reaction times. No correction was necessary in any of the experiments. We furthermore used planned comparisons within the above model wherever appropriate. Response errors were analyzed for each experiment using a chi-squared test for *relatedness* (related/control) and *wordness* (word/nonword).

2.3 Results

In each of the four experiments, two participants were excluded due to an equipment problem. In Experiment 1 (CVC SHORT > *LONG), a further five subjects were excluded from the analysis (incorrect responses >30%) and two targets had to be removed (incorrect responses >30%). In Experiment 2 (CVC LONG > *SHORT), one subject was removed from the analysis (incorrect responses >30%) and no word targets had to be excluded based on a larger number of errors. All reaction times outside ±2 standard deviations from the mean were excluded as outliers. Overall, 10.88% of the data was excluded from the analysis of Experiment 1 and 6.50% in Experiment 2.

*2.3.1 Experiment 1 (cvc SHORT – *LONG).* In this experiment, the CVC fragments from both the singleton real words and their geminate mispronunciations prime the full-word targets. While the mean reaction times were marginally faster for the related mispronounced geminate primes, there was no significant difference between singleton and geminate primes.

There was a significant main effect for *relatedness*, $F(1, 987.8) = 64.05$, $p < .001$, while *wordness*, $F(1, 987.2) = 0.11$, $p = 0.730$, and the interaction between *relatedness* and *wordness*, $F(1, 987.4) = 0.73$, $p = 0.391$, were not significant (*R*Square: 0.507). Thus, the short fragments of both the real-word singleton and the geminate mispronunciation ([kʰɔm]/*[kʰɔmː]) primed the full-word target ([kʰɔma]). A planned comparison test showed a significant priming effect for the real-word fragment, $t(987.5) = 5.04$, $p < .001$, as well as the mispronounced fragment, $t(987.5) = 6.28$, $p < .001$, compared with the controls. Thus, the fragment from the singleton real word as well as that from the geminate mispronunciation led to significant facilitation of the singleton-word target.

An error analysis for Experiment 1 (CVC SHORT > *LONG) showed an effect in the interaction between *relatedness* and *wordness*, $\chi^2(1) = 10.04$, $p = .0015$. Neither the test for *relatedness*,

Table 3. Summary of cvc fragment priming results (Experiments 1 & 2).

Condition	Prime	Target	RT (SEM)	Priming	*t* test	Error %
Fragment priming*: Experiment 1 (cvc short > *long)*						
Singleton	related	**[kʰɔm]**	ক্ষমা	544 ms (14.30)	39 ms*	*p* < .001	2.81
(word)	control	[dʒal]	[kʰɔma] 'forgiveness'	583 ms (14.40)			8.66
Geminate	related	***[kʰɔmː]**		538 ms (14.35)	48 ms*	*p* < .001	7.72
(nonword)	control	*[dʒalː]		586 ms (14.33)			4.95
Fragment priming*: Experiment 2 (cvc long > *short)*						
Geminate	related	**[bigː]**	বিজ্ঞান	494 ms (14.38)	87 ms*	*p* < .001	3.76
(word)	control	[manː]	[bigːæn] 'science'	581 ms (14.44)			8.54
Singleton	related	***[big]**		554 ms (14.49)	36 ms*	*p* < .001	9.01
(nonword)	control	*[man]		590 ms (14.42)			6.94

$\chi^2(1) = 1.75$, $p = .186$, nor that for *wordness*, $\chi^2(1) = 0.73$, $p = .393$, reached significance. The significance of the interaction results from a significantly lower number of errors in the related word (singleton) condition compared with its control condition only, $\chi^2(1) = 9.35$, $p = .0022$. A summary of results is provided in Table 3.

2.3.2 Experiment 2 (cvc long – *short). As in Experiment 1, both the real-word geminate fragments and the mispronounced singleton fragments showed priming compared with the control condition. However, in this experiment, the difference in reaction times (RT) between the real and the mispronounced fragments was significant ($p < 0.001$). Thus the real-word geminate fragments resulted in greater priming than the mispronounced singleton fragments.

The main effects for *relatedness*, $F(1, 1106) = 158.87$, $p < .001$, *wordness*, $F(1, 1104) = 33.81$, $p < .001$, and the interaction between *relatedness* and *wordness*, $F(1, 1105) = 16.27$, $p < .001$, were all highly significant (*R*Square: 0.495). Thus, the fragments of both the real-word geminate and the singleton mispronunciation ([bigː]/*[big]) primed the full-word target ([bigːæn]). A planned comparison test, however, showed a significant difference between the degree of priming of the real-word fragment and the mispronounced singleton fragment, $t(1105) = -7.007$, $p < .001$, in comparison with their controls. The initial CV segment of the mispronounced fragment [bi] was identical to the CV segment in the real-word geminate fragment, and this overlap explains the presence of a priming effect for the singleton fragment. It is, however, clear that the data in this experiment showed a markedly different pattern from that seen in Experiment 1 (cf. Figure 4).

The error analysis for Experiment 2 (cvc long > *short) again showed an interaction effect between *relatedness* and *wordness*, $\chi^2(1) = 6.50$, $p = .0108$. As in Experiment 1, neither the test for *relatedness*, $\chi^2(1) = 1.64$, $p = .199$, nor that for *wordness*, $\chi^2(1) = 2.36$, $p = .124$, reached significance. As in Experiment 1, the significance of the interaction results from a significantly lower number of errors in the related word (geminate) condition than in its control, $\chi^2(1) = 6.45$, $p = .011$.

When comparing Experiment 1 (short > *long cvc) with Experiment 2 (long > *short cvc) in a separate 3-way interaction analysis (*relatedness × wordness × experiment*, see Table 5 for details), we found the following pattern: Even though all related (real-word and mispronounced) primes facilitated the reaction to the target, there was a difference in the degree of priming of the geminate fragments depending on whether they were words or nonwords. The degree of priming was significantly larger in Experiment 2 than in Experiment 1 where geminate fragments are nonword fragments ($p < .001$). There was, however, no significant difference in priming between the experiments in the case of the singletons ($p = .5$).
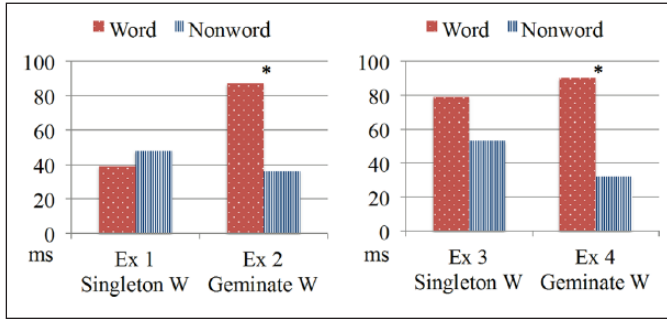
Figure 4. Comparison of the differences in degree of priming between words and nonwords in the CVC (1 & 2) and CVCV (3 & 4) fragment priming experiments.

2.3.3 Experiments 3 and 4 (cvc_v fragment). The results of Experiments 3 and 4 show the same patterns as those of Experiment 1 and 2 respectively (see Table 5 for full results). This shows that CVC segments with the full closure duration including the release already allow for correct segmentation and the additional information aids processing, resulting in faster response latencies in Experiments 3 and 4 compared with Experiments 1 and 2 (see Table 4). This did not, however, make a significant difference in this case. Note that the difference between the degrees of priming of the mispronounced and real-word fragments was not significant in Experiment 3, $t(1207) = 1.61$, $p = 0.108$, but was significant in Experiment 4, $t(1114) = -9.454$, $p \leqslant .001$.

In the error analysis for Experiment 3, relatedness was significant, $\chi^2(1) = 13.82$, $p = .0002$, due to fewer errors in the related conditions compared to their controls. In Experiment 4, none of the analyses reached significance.

In a comparison between the two cvc_v experiments (Experiments 3 & 4), there was a significant difference in the degree of priming for both geminates ($p < .001$) and singletons ($p < .001$). In both cases the real-word fragments primed significantly better than the nonword fragments (see Table 6 for details).

2.3.4 Comparisons across experiments. We furthermore conducted two additional three-way interaction analyses (*prime length × wordness × related*) to establish the effects of prime length (cvc vs. cvc_v) and consonant duration (singleton vs. geminate) on the degree of priming across Experiments 1 & 3 and 2 & 4. The results for these three-way interactions and individual contrasts are given in Table 6.

2.3.5 Prime length (cvc vs. cvc_v)

In the SHORT > *LONG experiments (1 & 3), there was no significant difference between the degree of priming for nonword geminates ($p = .635$), but there was a significant difference in the case of the singleton real words ($p < .001$) with the longer singleton primes (Experiment 3 cvc) priming significantly better than their shorter counterparts in Experiment 1.

The data in the LONG > *SHORT experiments (2 & 4) showed no significant difference between the degree of priming for geminate real words ($p = .695$) and singleton nonwords ($p = .269$).

2.4 Discussion

One of the key questions this set of experiments intended to investigate was whether form fragment priming would show a symmetric or asymmetric pattern of facilitation, which would

Table 4. Summary of cvc_v fragment priming results (Experiments 3 & 4).

Condition		Prime	Target	RT (SEM)	Priming	t test	Error %
Fragment priming: *Experiment 3* (cvc$_v$ SHORT > *LONG)							
Singleton	related	**[kʰɔm$_v$]**	ক্ষমা	493 ms (10.45)	79 ms*	p < .001	1.80
(word)	control	[ʤal$_v$]	[kʰɔma] 'forgiveness'	572 ms (10.47)			3.59
Geminate	related	*[kʰɔm:$_v$]		503 ms (10.46)	53 ms*	p < .001	3.57
(nonword)	control	*[ʤal:$_v$]		556 ms (10.49)			4.79
Fragment priming: *Experiment 4* (cvc$_v$ LONG > *SHORT)							
Geminate	related	**[big:$_v$]**	বিজ্ঞান	481 ms (13.24)	90 ms*	p < .001	2.54
(word)	control	[man:$_v$]	[big:æn] 'science'	571 ms (13.29)			6.33
Singleton	related	*[big$_v$]		548 ms (13.26)	32 ms*	p < .001	2.24
(nonword)	control	*[man$_v$]		580 ms (13.32)			7.03

Table 5. Full results for Experiments 3 and 4.

Experiment 3 (cvc$_v$ SHORT > *LONG)			
relatedness	$F(1, 1207)$	= 200.55	p < .001*
wordness	$F(1, 1206)$	= 0.37	p = .546
wordness × relatedness	$F(1, 1207)$	= 8.23	p = .004*
Planned comparison: **singletons** (control **w** − related **w**)	$t(1207)$	= 12.08	p < .001*
Planned comparison: **geminates** (control **nw** − related **nw**)	$t(1207)$	= 7.96	p < .001*
Planned comparison: related items (geminate nw − singleton w)	$t(1207)$	= −9.45	**p = .108**
Experiment 4 (cvc$_v$ LONG > *SHORT)			
relatedness	$F(1, 1115)$	= 144.10	p < .001*
wordness	$F(1, 1114)$	= 56.95	p < .001*
wordness × relatedness	$F(1, 1114)$	= 31.84	p < .001*
Planned comparison: **geminates** (control **w** − related **w**)	$t(1114)$	= −4.49	p < .001*
Planned comparison: **singletons** (control **nw** − related **nw**)	$t(1114)$	= 12.56	p < .001*
Planned comparison: related items (geminate w − singleton nw)	$t(1114)$	= −9.45	**p < .001***

allow us to draw conclusions about the representation of duration in the lexicon. Furthermore, two different durations of the fragments were used in order to determine whether listeners are able to correctly identify the consonant of these fragments with the closure duration alone or whether the addition of the first two glottal pulses (average of 16 ms) of the following vowel significantly improves the listeners' performance. Recall that in the gating study, Lahiri and Marslen-Wilson (1992) noted that the release of the consonant led to a significant increase in correct responses.

The results from Experiment 1 (cvc) showed that both real-word and mispronounced fragments prime the target equally well. There was no significant difference in the degree of priming between the real-word singleton fragment and the mispronounced geminate fragment. Experiment 2 (cvc) also showed significant priming in both the real word and mispronounced word conditions, but the difference between the degrees of priming of the real-word geminate fragment and the mispronounced singleton fragment was highly significant (51 ms). This showed a distinction between the mispronunciation and the real word, with the mispronunciation priming to a lesser degree, a finding which will be explored further in the semantic priming experiments below. The

Table 6. Comparison across form-priming experiments.

Comparison of wordness

Experiments 1 & 2 (CVC SHORT > *LONG & CVC LONG > *SHORT)			
experiment × wordness × relatedness	$F(1, 2092)$	= 4.74	$p = .030*$
Planned comparison: **singletons** *(control – related)*	$t(2238)$	= 0.59	$p = .554$
Planned comparison: **geminates** *(control – related)*	$t(2238)$	= 3.68	$p < .001*$
Experiments 3 & 4 (CVC$_v$ SHORT > *LONG & CVC$_v$ LONG > *SHORT)			
experiment × wordness × relatedness	$F(1, 2321)$	= 37.28	$p < .001*$
Planned comparison: **singletons** *(control – related)*	$t(2473)$	= −4.82	$p < .001*$
Planned comparison: **geminates** *(control – related)*	$t(2473)$	= 3.79	$p < .001*$
Comparison of prime length			
Experiments 1 & 3 (CVC & CVC$_v$ SHORT > *LONG)			
experiment × wordness × relatedness	$F(1, 2214)$	= 6.92	$p = .009*$
Planned comparison: **singletons** *(control – related)*	$t(2342)$	= −4.2	$p < .001*$
Planned comparison: **geminates** *(control – related)*	$t(2342)$	= −0.47	$p = .636$
Experiments 2 & 4 (CVC & CVC$_v$ LONG > *SHORT)			
experiment × wordness × relatedness	$F(1, 2240)$	= 1.13	$p = .288$
Planned comparison: **singletons** *(control – related)*	$t(2369)$	= 1.10	$p = .269$
Planned comparison: **geminates** *(control – related)*	$t(2369)$	= −0.39	$p = .695$

results of Experiments 3 and 4 (CVC$_v$ fragment) provide further evidence of the same nature, as the patterns of facilitation are very similar to those of the CVC fragment priming and do produce an improvement in response latencies due to the inclusion of the additional vowel information but no change of the pattern found in Experiments 1 and 2, as suggested by the results in the Lahiri and Marslen-Wilson gating study (1992).

From our predictions, we would have expected either symmetrical identity priming only (for a featural representation) or an asymmetric pattern where a geminate can replace a singleton but not vice versa. We seem to see neither pattern clearly in the data, but instead find symmetrical priming in all conditions. There is, however, a difference between the degree of facilitation provided by real-word primes in comparison with mispronounced primes in the LONG > *SHORT experiments (2 & 4) which is not evident in Experiments 1 and 3. This would fit with a moraic representation account, since the lack of a mora in the acoustic signal would not lead to full lexical access. Since the priming effects we see in the data could be attributed solely to the large featural overlap between prime and target, further evidence is required to investigate whether the asymmetric difference in the degree of priming is a true processing asymmetry.

3 Semantic priming experiments (Experiments 5 & 6)

To determine what causes the asymmetric pattern observed in the fragment priming data, two semantic priming experiments (Experiments 5 & 6) were designed on the basis of the form-priming tasks (Experiments 1–4). Two major changes to the experimental paradigm are of note: firstly, listeners are now presented with full words rather than fragments, and secondly, the prime must be able to activate semantically related items to lead to facilitation and therefore full lexical access must be achieved. Full-word priming was used to ensure that listeners were able to construct a complete prosodic interpretation containing all structural information. This will show whether the effect observed in the fragment priming experiments disappears as soon as the complete structural

information is available and full lexical access is necessary. Will we find symmetric identity priming only or will the asymmetric pattern persist? Experiments with featural contrasts have shown that, if both features are specified in the lexical representation, the results show a symmetric pattern since there is a mismatch in both directions (see Cornell et al., 2013 for an MMN study). The ERP study introduced in the introduction, which used the same semantic priming design, found an asymmetric pattern of results with geminates being tolerated instead of singletons (showing a decreased N400) while the results for singletons in the place of geminates were no different from those for control pairs (Roberts et al., 2014).

Experiment 5 (SHORT > *LONG) is constructed using full-word primes of the fragments used in Experiments 1 and 3 (e.g., [khɔma] 'forgiveness'/ *[kʰɔmːa]) but with a target which is semantically related to the real words ([marjona] মার্জনা 'forgiveness'). Experiment 6 (LONG > *SHORT) is based on Experiments 2 and 4 (e.g., [bigːæn] 'science'/*[bigæn]; Target: [gɔbeʃɔna] গবেষণা 'science'). Relatedness judgments were obtained for all prime–target combinations as well as all control–target combinations, and results are reported below.

3.1 Semantic priming predictions

Our form-priming tasks focus rather closely on the segmental information since participants do not hear full words. To ensure that full lexical access is being achieved, we constructed a similar mispronunciation task using full words with semantically related targets. The full-word task removes any ambiguity in the acoustic signal about the status of the medial consonant.

If all mispronunciations symmetrically fail to activate the real word (and thus do not facilitate the reaction to the target), one could infer that the contrast is indeed on the featural level since a representation with [-LONG] should not activate one containing [+LONG] and vice versa. The moraic representational hypothesis, however, would predict that a geminate mispronunciation of a singleton would not inhibit access of the real word while a singleton mispronunciation of a geminate real word would. A word with a geminate medial consonant will be represented with an additional mora, and a singleton mispronunciation would not include the moraic representation required to activate the geminate real word and should thus not lead to facilitation of the semantically related target. When a geminate mispronunciation is used to prime a real-word singleton, all information necessary to activate the singleton real word is present and it should thus result in facilitation as there is nothing in the representation with which the mora extracted from the auditory signal can mismatch.

Asymmetric activation of this type has previously been found in perception studies of featural contrasts (see among others Cornell et al., 2011; Eulitz & Lahiri, 2004; Roberts et al., 2013, 2014). Indeed, perceptual asymmetries are not only observed in linguistic contexts but also occur in many other categorical discrimination tasks in both visual and auditory domains (see for example Cusack & Carlyon, 2003; Treisman & Gormican, 1988). For example, the letter Q is much more easily detected in a field of Os than the letter O is in a field of Qs, where a serial search has to be performed, and this pop-out effect is well attested across domains. This shows that certain characteristics create asymmetric perception patterns, with deviation in one direction (i.e., from O to Q) more easily detectable than deviation in the other (from Q to O).

While models like TRACE (Mayor & Plunkett, 2013; McClelland & Elman, 1986) would assume that no mispronunciations are tolerated as they propose a featural mismatch in both directions, models of sparse specification (e.g., FUL; Lahiri & Reetz 2010), which assume that only non-predictable information is specified and stored in the mental lexicon, would be more likely to predict a processing asymmetry. These models are built on the premise that in speech perception the brain utilizes asymmetries inherent in language to its advantage. Several studies have found evidence for the specification and underspecification of features such as the underspecification of the place of articulation

feature [coronal] (Eulitz & Lahiri, 2004; Friedrich et al., 2008; Roberts et al., 2013; Scharinger and Lahiri, 2010) and of the manner of articulation feature [plosive] (Cornell et al., 2011).

3.2 Method and materials

3.2.1 Participants. Ninety female native speakers of Bengali (aged 18–23; mean average age 19.67), all undergraduate students at Gokhale Memorial Girls' College (Kolkata), took part in the experiments. All participants had corrected-to-normal vision and no hearing (or other) impairments. The participants were compensated for their participation according to the rules of the college.

3.2.2 Primes. Each experiment consisted of 72 trials differentiated by two conditions: relatedness (*semantically related* or *unrelated*) and wordness (*real word* or *mispronunciation*). Since there was no need to control whether the CVC fragments of the primes were words in their own right, the semantic priming experiments consist of 36 related prime–target pairs. All 24 primes used in the form-priming experiment were used and 12 additional, structurally identical words were chosen. Frequency and familiarity measures for these additional primes were measured and are reported for the form-priming experiments. As in Experiments 1–4, a corresponding mispronunciation was recorded (*[bigæn]; *[kʰɔmːa]) for each word prime. The recording procedure was the same as for the earlier experiments since all auditory stimuli were recorded in one session.

3.2.3 Targets. All real-word targets were semantically related to the real-word primes (e.g., [bigːæn] 'science' to [gɔbeʃɔna] 'science'; [kʰɔma] 'forgiveness' to [marjona] 'forgiveness'), and whenever possible the prime–target pairs were synonyms between one and three syllables in length with numbers of syllables balanced across experiments. All 36 word targets were also paired with unrelated control primes and their mispronunciations (see Table 7). In addition to the 36 real words, 36 nonword targets were created and matched with disyllabic real-word primes and their mispronunciations created using the same manipulation as in the test primes (geminate vs. singleton).

3.2.4 Procedure. The experimental set-up was identical to that in the form-priming experiments. The same equipment was used and we followed the same procedure.

3.2.5 Relatedness rating. When conducting the frequency and familiarity rating tasks, a *semantic relatedness* task was also administered. In this task, words were presented in pairs and participants were asked to rate them on a 7-point scale ranging from completely unrelated (1) to very closely related (7). In addition to all test prime–target and control prime–target combinations, we also introduced 36 somewhat related pairs to avoid floor or ceiling effects. These pairs were the same in both questionnaires. Due to the large number of pairs, the stimuli were once again divided randomly into two lists. As the ratings for Experiments 5 and 6 were obtained at the same time, the number of geminate and singleton words was controlled for across the two questionnaires. To avoid order effects in the ratings, each of the two questionnaires was pseudo-randomized twice and presented to participants in two different orders. Each of the four questionnaires was completed by 15 subjects, resulting in 30 rankings for each word pair (see Table 8). Only pairs with a score greater than six for test items and lower than two for control items were included in the study.

3.3 Results

Three participants' data was discounted for both analyses due to technical failure. In Experiment 5 (ꜱʜᴏʀᴛ > *ʟᴏɴɢ), we excluded one target (incorrect responses in over 25% of trials) and three

Table 7. Prime–target combinations and predictions for Experiments 5 and 6.

Condition	Prime		Target	Competing Hypotheses	
				Symmetry	Asymmetry
***Semantic priming**: Experiment 5 (SHORT > *LONG)*					
Singleton (word)	related	**[kʰɔma]** 'forgiveness'	মার্জনা [marjona] 'forgiveness'	√	√
	control	[ʤala] 'burn'			
Geminate (nonword)	related	***[kʰɔmːa]**		X	√
	control	*[ʤalːa]			
***Semantic priming**: Experiment 6 (LONG > *SHORT)*					
Geminate (word)	related	**[bigːæn]** 'science'	গবেষণা [gɔbeʃɔna] 'science'	√	√
	control	[manːo] 'respectable man'			
Singleton (nonword)	related	***[bigæn]**		X	X
	control	*[mano]			

Table 8. Results of relatedness rating questionnaire.

	Relatedness Rating (1–7)	
	TPrime–Target	CPrime–Target
Ex 5	6.65	1.03
Ex 6	6.56	1.14

subjects whose error rates were greater than 25%. Two subjects were excluded in Experiment 6 (LONG > *SHORT) (incorrect responses >25%) along with three targets (incorrect responses >25%). In addition, RT outside ±2 standard deviations of the mean were excluded as outliers. Overall, in Experiment 5 we excluded 6.60% of the data and in Experiment 6, 7.88% of data was excluded.

*3.3.1 Experiment 5 (SHORT > *LONG).* Reaction times were faster both for targets with related real-word primes and mispronunciations of related real words than for control primes. There was a slight difference between the real-word primes and their mispronunciations, with the real-word primes resulting in marginally faster RTs. The data was analyzed using the methods described in 2.2.7.

There was a significant main effect for *relatedness*, $F(1, 2371) = 54.13$, $p < .001$, but not for *wordness*, $F(1, 2371) = 0.62$, $p = 0.431$ (*R*Square: 0.450). Thus, although the RT to the controls were slower than to the related primes, there was no difference between the singleton-word and geminate-nonword primes. There was also a significant interaction of *wordness × relatedness*, $F(1, 2371) = 7.48$, $p = .006$. Planned comparisons, however, showed no difference between the related word (singleton) and related nonword (geminate) conditions. They further showed that the difference between the singleton related word and control was highly significant, $t(2371) = 7.14$, $p < .001$, as was the difference between the geminate *nonword* and its control, $t(2371) = 3.27$, $p < .001$. Thus, both the singleton real word and its geminate mispronunciation triggered semantic priming.
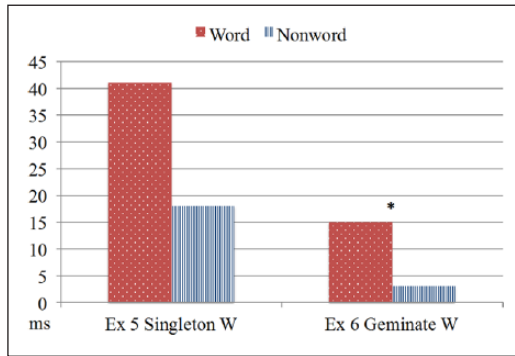
Figure 5. Comparison of the differences in degree of priming between words and nonwords in the semantic priming experiments (5 & 6).

The significance of the interaction stems from a difference in the control conditions. The singleton (word) control condition is significantly slower than the geminate (nonword) control condition, $t(2372) = -2.46$, $p = .014$ (see also Table 9).

The error analysis showed a significant difference between the number of errors in the related vs. unrelated conditions, $\chi^2(1) = 5.93$, $p \leqslant .015$, but no difference between the word (singleton) and nonword (geminate) conditions, $\chi^2(1) = 0.36$, $p = .551$. This is in line with the results above, showing equal facilitation for real-word and mispronounced primes.

3.3.2 Experiment 6 (LONG > *SHORT). There was again a significant main effect of *relatedness*, $F(1, 2297) = 6.59$, $p = .010$, and *wordness*, $F(1, 2299) = 4.37$, $p = .037$, but the interaction between *relatedness* and *wordness* did not reach significance, $F(1, 2297) = 2.85$, $p = .092$ (*R*Square: 0.483). Planned comparisons showed a significant between controls and related primes effect for real words (geminates; $t(2297) = 3.03$, $p = .003$), but not for mispronunciations (singletons; $t(2297) = 0.62$, $p = 0.537$). Thus, only the real geminate words triggered semantic priming, while the singleton mispronunciations did not differ significantly from the controls (cf. Figure 5).

An error analysis for Experiment 6 (LONG > *SHORT) showed an effect for relatedness, $\chi^2(1) = 8.08$, $p = .005$, with a significantly larger percentage of errors in the unrelated condition but no effect of wordness, $\chi^2(1) = 2.83$, $p = .093$. The interaction between relatedness and wordness was not significant, $\chi^2(1) = 0.55$, $p = .460$.

3.3.3 Comparison across experiments. In addition to the analyses above, we ran a separate linear mixed model across both experiments with the fixed effects *relatedness* (related/control), *wordness* (word/nonword prime) and *experiment* (SHORT > *LONG / LONG > *SHORT) with subjects and items included in the model as random effects. The three-way interaction *relatedness × wordness × experiment* was significant, $F(1, 4556) = 9.14$, $p = .003$. We then conducted contrasts to determine how the degree of priming by geminates and singletons compares across experiments.

When comparing the effect of closure duration across experiments, the degree of facilitation after geminate primes did not differ significantly between Experiments 5 and 6 despite the fact that geminates are nonwords in Experiment 5, $t(4768) = 0.61$, $p = 0.542$. The singleton data showed a significant difference between the facilitation after singleton-word primes in Experiment 5 and that after singleton nonword primes in Experiment 6, $t(4768) = 4.87$, $p < .001$, with the word primes in Experiment 5 resulting in facilitation while the nonword primes in Experiment 6 did not (see Table 10).

Table 9. Summary of semantic priming results.

Condition		Prime	Prime	RT (SEM)	Priming	*t* test	Error %
Semantic priming: Experiment 5 (SHORT > *LONG)							
Singleton (word)	related	**[kʰɔma]** 'forgiveness'	মার্জনা [marjona] 'forgiveness'	610 ms (12.83)	41 ms*	< .001	4.65
	control	[dʒala] 'burn'		651 ms (12.86)			7.61
Geminate (nonword)	related	***[kʰɔmːa]**		618 ms (12.83)	18 ms*	= .001	4.52
	control	*[dʒalːa]		636 ms (12.86)			6.04
Semantic priming: Experiment 6 (LONG > *SHORT)							
Geminate (word)	related	**[bigːæn]** 'science'	গবেষণা [gɔbeʃɔna] 'science'	601 ms (11.82)	15 ms*	= .003	2.96
	control	[manːo] 'respectable man'		616 ms (11.84)			5.81
Singleton (nonword)	related	***[bigæn]**		615 ms (11.84)	3 ms	= .537	4.61
	control	*[mano]		618 ms (11.85)			6.68

Table 10. Comparison across semantic priming experiments.

Experiment 5 & 6 (full-word semantic priming)			
experiment × wordness × relatedness	*F*(1, 4556)	= 9.14	*p* = .003*
Planned comparison: singletons *(control − related)*	*t*(4768)	= 4.57	*p* < .001*
Planned comparison: geminates *(control − related)*	*t*(4768)	= 0.61	*p* = .542

3.4 Discussion

It is evident from the above analyses that both experiments show strong semantic priming effects for both geminate and singleton real words; for example, [bigːæn] 'science' primes [gɔbeʃɔna] 'science' and [kʰɔma] 'forgiveness' primes [marjona] 'forgiveness'. Furthermore, in Experiment 5 (SHORT > *LONG) the geminate mispronunciations of the real-word primes (*[kʰɔmːa] from [kʰɔma]) also lead to faster RT than their controls (*[dʒalːa]), while this is not the case in Experiment 6 where we find identity priming only (cf. Figure 5).

This pattern of results is in line with the predictions set out above for a moraic representation account. The data provides evidence for an approach which assumes that only the geminate consonant has a specific representation in the lexicon while the singleton is underspecified. Thus the acoustic signal of the geminate mispronunciation *[kʰɔmːa] allows for the extraction of a mora which is not required by the lexical representation of the singleton [kʰɔma] 'forgiveness'. This, however, does not result in a conflict since the singleton does not have a specification of its own with which the additional mora could mismatch. In Experiment 6, we see the inverse case: the lexical representation of the real-word geminate [bigːæn] 'science' is specified for duration (with an additional mora) but the singleton mispronunciation *[bigæn] does not allow the listener to construct this additional mora from the acoustic signal, and this results in a mismatch which leads to non-activation of the real-word geminate (and therefore the semantically related target).

4 General discussion

We have reported six experiments using a lexical decision task with form priming and semantic priming to investigate the processing of the geminate–singleton contrast in Bengali, to allow us to choose between two theoretical representational accounts of this contrast. The issues we are concerned with here are the following: given that the primary acoustic cue for the geminate–singleton contrast is closure duration, to what extent is it acceptable when this duration is switched, turning a real word into a nonword? If the resulting mispronunciation is accepted by the listener, will this be the case in both directions or is the pattern asymmetric? The moraic representation of geminates predicts an asymmetry while the featural representation would predict symmetrical identity priming. The results from both form and semantic priming studies clearly show that there is an asymmetry in the processing of singletons versus geminates.

We proposed two possible hypotheses based on previous experimental and theoretical research on geminates as well as phonological theory: one where the difference between geminates and singletons is encoded on the featural level, and one which is based on moraic theory and weight representations on the skeletal level. As we outlined in the predictions, these two hypotheses would necessarily result in different processing consequences which should be observable in the results of an online lexical decision task. Both hypotheses will be re-evaluated in light of the form priming and then the semantic priming experiments.

4.1 Form priming

The present study therefore conducted two form-priming experiments with fragments of two different durations (CVC and CVC$_v$ – corresponding to gates 3 and 4 in the gating study) with the aim of answering two different questions: Firstly, is the switch of the closure duration of geminates and singletons equally acceptable/unacceptable in both directions or is there an asymmetry? Secondly, does the information provided by the two additional glottal pulses of the following vowel (Experiment 3 & 4) influence the perception and therefore the processing of the durational contrast?

Since there is a fundamental difference in syllable structure between geminates and singletons in Bengali (see (1)), it must be crucial for the listener to be able to determine whether the medial segment is long or short to be able to build the correct syllable structure. As the additional two glottal pulses in the CVC$_v$ experiments make the duration of the medial consonant unambiguous, we may expect greater accuracy for real-word fragments in the participants' responses, and possibly a pattern which differs from that observed in the CVC experiments, with mispronounced words being more readily identified as such.

Our results show that, in all four experiments, both real-word and mispronounced fragments result in significant facilitation of the target irrespective of the duration of the medial consonant. However, in the set of experiments where real-word geminates are changed to singletons (Experiments 2 & 4), there is a significant difference between the degree of priming of the real-word geminates and that of the mispronounced singletons. The real-word fragments lead to significantly greater facilitation of the target. When comparing across all four experiments, the SHORT > *LONG experiment also shows a significant difference between the degree of priming, with singleton real-word fragments priming better than geminate mispronunciations. The effect of prime length (CVC vs. CVC$_v$) results in a significant difference in the case of the singleton real words only when comparing Experiments 1 and 3. When the additional two glottal pulses are included in the fragment prime, there is greater facilitation of the target than in the case of the shorter CVC fragment.

In terms of the two competing representational hypotheses presented earlier, this data in itself does not yet yield conclusive results in either direction. There is symmetrical facilitation resulting from primes across all conditions but there are differences in the degree of priming which warrant further investigation. The results of these tasks alone could be influenced by task-based biases since, in a form-priming task, the matching featural information alone may be enough to result in priming. The asymmetric effect found in Experiments 2 and 4 may be one which is generated by factors such as cohort size rather than a difference in the representation of geminates and singletons. To examine whether these results are indeed indicative of a difference in representation and processing rather an effect of task or cohort size, we designed a semantic priming task with the same words.

4.2 Semantic priming

The acoustic information in this task was unambiguous with regard to the status of the medial consonant. Thus effects resulting from a lack of information on which syllable structure to build should not influence the results of this task. Furthermore, the task requires full lexical access, which reduces the reliance on matching featural information which could have been a potential confound in the previous four experiments.

The results of the semantic priming show a pattern of asymmetric activation, with both real-word singletons and mispronounced geminates priming the target in Experiment 5 but only geminate real words resulting in facilitation in Experiment 6. In addition to this, a comparison across experiments shows that there is no significant difference between the degree of priming after a geminate nonword fragment in Experiment 5 and a geminate real-word fragment in Experiment 6.

Which of the two hypotheses concerning the representation of consonant duration better accounts for this pattern of results? Recall that we introduced two ways of distinguishing singletons from geminates—by the feature [+/-LONG] on the segmental level or by an independent prosodic tier where geminates are represented by a mora μ and singletons have no additional representation (see Figure 2). As we state in our predictions, if [+LONG] and [-LONG] are both specified then we would predict identity priming only, since the features in the representations would mismatch both ways. A geminate prime containing the feature [+LONG] should not be able to activate a singleton word since its representation contains the feature [-LONG], which would result in a mismatch. The same would also hold in the other direction. However, while the fragment priming data shows some symmetry in the activation patterns, the semantic priming data, with its very clear asymmetry, is incompatible with this approach.

Instead, the data in this study is better explained by an approach which assumes that the singleton–geminate contrast is made on an independent tier. Moraic theory proposes an additional mora (μ) on the prosodic tier of words with a medial geminate (see Figure 2). Thus the prosodic information of a word form like [ʃun:o] is specified as a geminate, for example, the /n:/ has an inherent μ. It follows that if some value is specified on the prosodic level, only an input that satisfies this specification will match and lead to activation. Lexical entries of words that lack specification for consonant length on this level (e.g., words with a medial singleton which have no additional mora, such as [ʃona]) can be activated by input that matches on the feature level but does not match on the prosodic level (e.g., *[ʃon:a]), since there is nothing in these entries to indicate a mismatch with the input. The semantic priming experiments show that geminate mispronunciations result in the activation of the corresponding singleton word and thus its semantic relations. This is not the case for singleton mispronunciations. Since a geminate mispronunciation contains additional duration information, it subsumes the singleton real-word representation because all other (featural) information is identical. However, when a singleton mispronunciation is heard in the place of a

geminate, the mora necessary for the match with a geminate representation cannot be generated from the duration extracted from the acoustic signal and thus activation fails.

The findings of the present study indicate that the geminate–singleton contrast stems from a difference in lexical specification: geminates are specified by an additional mora while singletons are not. We propose that this specification makes up part of the metrical shape of a word form together with lexical stress and/or lexical accent—depending on the language and the particular word in question. This is not a question of an accidental gap in the singleton representation (which does not contain a mora), but of not specifying any more information than is absolutely necessary to achieve unambiguous identification. This theoretical standpoint is consistent with most recent phonological approaches including the FUL which do not assume length as a phonological feature (see Gussenhoven & Jacobs, 2011 and references therein).

One of the fundamental questions in speech perception is how the perceptual system of a listener copes with the enormous variability in the speech input, both in cases of rule-governed variation and those of genuine mispronunciation. The question we addressed in this paper is how variation in consonantal duration in the speech signal is resolved, focusing on a language where duration is used contrastively to distinguish phonemes. What could be a plausible strategy to help listeners minimize perception errors and assist in detecting phonemes? Our results suggest that one strategy is to keep contrast sensitivity asymmetric, whereby it is easier to correctly detect a singleton mispronounced as a geminate than vice versa. A prerequisite for asymmetric contrast sensitivity is that not all aspects of the contrast are represented in the mental lexicon. This is perhaps not surprising, since many language universals and their implications are asymmetric and unidirectional; for example, the presence of nasal vowels implies the existence of oral vowels while the reverse is not the case. Similarly, geminate consonants imply the presence of singletons. Furthermore, certain phonological processes show asymmetrical patterns; for example, vowel nasalization occurs in a nasal context only but denasalization of vowels is usually context-free. It is thus not surprising that processing asymmetries also exist.

Such processing asymmetries have been found for certain segmental contrasts. For example, a range of experiments on place of articulation features show asymmetric patterns suggesting that CORONAL is underspecified while DORSAL and LABIAL are not (e.g., Cornell et al., 2011 and Eulitz & Lahiri, 2004 on vowels; Friedrich et al., 2008 and Roberts et al., 2013 on consonants). There is less evidence for similar processing asymmetries for prosodic features such as tonal accent and duration. One piece of evidence is available from the processing of Swedish accents where one accent is assumed to be specified (e.g., Accent 1) while the other is underspecified (Accent 2) (Felder et al., 2009). Our results here show a similar pattern for duration contrast. The data supports the idea that the perceptual system refers to an asymmetric representation for a true phonemic length contrast (in languages like Bengali), where a geminate consonant is specified for its length with a mora while a singleton is not, leading to an asymmetry in processing.

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Notes

1   If not mentioned otherwise, Bengali refers to the language spoken in West Bengal, India. Another term for this variety is Standard Colloquial Bengali (Chatterji, 1926).
2   An asterisk * before a word indicates that it is not an existing lexical item.
3   A three-way contrast in consonant length is sometimes proposed for Finno-Ugric languages (e.g., Estonian).
4   There is evidence that sometimes these two types of geminates behave in an identical fashion. For instance, from Old to Middle English, all geminates medially and finally were degeminated regardless of whether they were underlying geminates or derived by a sequence of identical consonants; for example, underlying geminate *bedd > bed* 'bed', vs. concatenated *bled-de > bled (blēd-de > bledde)* 'bled' (see also Davis, 2011; Hayes, 1986; and Schein & Steriade, 1986, for other examples).
5   Davis (2011) suggests a dual representation, which was also advocated by Lahiri and Koreman (1988) for Dutch long vowels, which would then have a parallel structure with a long vowel being bimoraic. These authors claimed that long vowels in Dutch were not necessarily bimoraic while ambisyllabic single consonants closed a syllable and the coda obtained a mora by weight by position, which made the syllable heavy and attracted stress. The way in which one could differentiate geminates which do carry weight and those that do not is shown in the figure below.
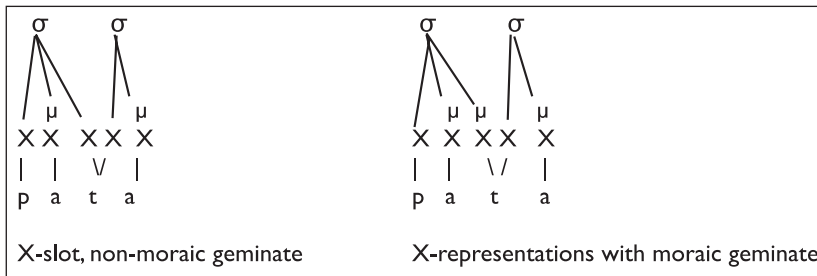
6   There are two exceptions: The voiced retroflex only occurs as a geminate word-medially and does not have a singleton counterpart, and the voiced aspirate retroflex does not occur word-medially (changes to [r] as a singleton).

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