**Voiceless Nasals in Auditory Phonology**
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Löfqvist (1980) suggests that for each supralaryngeal configuration there is, more or less, a corresponding laryngeal target. And since the larynx and the supralaryngeal articulators are more or less independent of each other, we may assume that any given laryngeal target has a particular *functional* goal, and isn't merely an automatic consequence of the supralaryngeal configuration. For example, plain intervocalic voiceless stops are often accompanied by a laryngeal abduction. Far from being an automatic consequence of a stop, a spread glottis here serves the functional role of inhibiting the voicing that might otherwise occur throughout a sufficiently brief oral closure, thus potentially salvaging a contrast between voiceless and voiced stops.

However, laryngeal gestures may also possess contrastive status in and of themselves, and similarly, are often associated with particular supraglottal configurations. In this paper, I discuss how spreading the glottis during a nasal stop contributes to the achievement of a potentially contrastive acoustic state. In particular I investigate the timing of this laryngeal gesture with respect to the nasal stop -- these are so-called "voiceless" and "breathy" nasals -- and how certain particular timings here serve to better encode the relevant acoustic information at the level of the peripheral auditory system.

My claims, then, are that different timings of articulatory gestures with respect to one another culminate in better or worse percepts. The better the percept, the less common the pattern, and the worse the percept, the more common the pattern. Optimal timing patterns correlate with degree of auditory nerve response: the greater the auditory nerve response, the less common the pattern, and the lesser the auditory nerve response, the more common the pattern. A functional link may thus be established between recoverability and cross-linguistic tendencies.

Consider first how place of articulation is cued in a plain nasal. Pooling the results of several studies (Fant 1960, Fujimura 1962, Recasens 1983, Dantsuji 1984, 1986, 1987, Kurowski and Blumstein 1984, Bhaskararao and Ladefoged 1991), it seems that **CV** formant transitions are primary in conveying place information, **VC** formant transitions are secondary, and nasal murmur formants tertiary. Here, the steady state portion of the nasal, often called the nasal murmur, contains place cues primarily in the form of a nasal zero, or anti-resonance: a frequency range of dampened energy. In Burmese and Catalan, for example, studies show that the murmur itself can help to cue place of articulation (Dantsuji 1984, 1986, 1987; Recasens 1983). The farther back in the oral cavity the constriction, the higher in frequency is this reduction in energy. Moreover, nasality as a class may be cued by both a low frequency formant, and a mid-range energy plateau. So intervocalic nasals, for example, ama, ana, aɲa, enjoy an abundance of cues, and not coincidentally, are never subject to neutralization.

Now, if a spread glottis is implemented simultaneously with a nasal stop (aṇa, aṃa, aŋa) what are the acoustic consequences? Again, pooling the results of several researchers (Ohala 1975, Dantsuji 1984, 1986, 1987, Ladefoged and Maddieson 1996), **CV** formant transitions would be obscured, **VC** formant transitions would be obscured, and nasal murmur formants would be obscured. This, of course, is a most undesirable result, because the functional gain of adding the aspiration is lost by losing oral place contrasts.

Instead, the spread glottis is normally timed to the early portion of the nasal stop. In this fashion, a partial nasal murmur survives, and most importantly, **CV** transitions survive as well, and so all place information is recoverable. In Burmese for example, we find aN̥ma, aN̥na, and aN̥ŋa. The typology of voiceless nasals can be accounted for by the salience of contrastive cues. Henderson (1985), for example, reports that voiceless nasals of the Burmese type are cross-linguistically more common than nasals and laryngeal abductions which possess other timing relationships with respect to each other.

But why should this be the canonical realization of voiceless nasals? Relatedly, why are **CV** transitions especially important? The answer I would like to suggest derives from certain neurological facts about the peripheral auditory system. Briefly, Bladon (1986) discusses some of the major principles of what he terms "auditory phonetics." For present purposes, the two principles in (1) are most relevant.
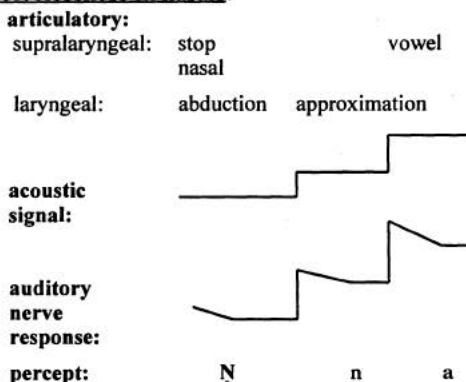
(1)     **On/off response asymmetry**: spectral changes whose response in the auditory nerve is predominantly an onset of firing are much more perceptually salient than those producing an offset (Tyler, Summerfield, Wood, and Fernandez 1982).
**Short-term adaptation**: after a rapid onset of auditory nerve discharge at a particular frequency, there is a decay to a moderate level of discharge, even though the same speech sound is continuing to be produced (Delgutte 1982).

The generalization here is that acoustic signals that involve abrupt increases in acoustic energy trigger maximal auditory nerve response, and presumably result in better percepts.

In (2), I provide a schematic of the articulatory and acoustic properties of the canonical voiceless nasal, and most importantly, the distorting effect imparted by the auditory nerve. Observe that sudden increases in energy -- from voiceless nasal flow, to nasal murmur, to vowel -- results in a heightened neural response, which, again, presumably results in a better percept.

(2)     Gross schematic of articulatory, acoustic, and auditory characteristics of early voicelessness in nasals:



**articulatory:**
supralaryngeal:     stop        vowel
                    nasal

laryngeal:          abduction   approximation

**acoustic signal:**

**auditory nerve response:**

**percept:**        N̥          n           a

So let's look at Burmese in some detail. In (3) are pairs which minimally contrast for voicelessness.

(3)  voiced nasals:                    voiceless nasals:
    mâ̤   lift up              N̥mâ̤   from
    na    pain                 N̥na    nose
    ɲa    right                N̥ɲa    considerate
    ŋâ    fish                 N̥ŋâ    borrow

Far more interesting are the forms in (4), taken from Okell's (1969) grammar. Voicelessness here is not only lexical, but serves a morphological purpose as well, producing active verbs. These are termed "h/non-h pairs" by Okell. In (4a) are plosives. Note that aspiration here is realized at stop release, *after* the oral occlusion which, as I've argued elsewhere (along with Kingston 1985, 1990), is the optimal realization of oral stops modified by glottal spreading. In (4b), the linear ordering of the breath morpheme is *preceding* the plain voiced nasal. So, whether plosive-initial or nasal-initial, the breath morpheme is optimally timed with respect to its affiliated supralaryngeal gesture.

(4)  morphological aspiration (h/non-h pairs -- Okell 1969):
    a.  obstruent-initial:
        pi     be pressed            pʰi     press, compress
        pe     break off, be chipped pʰe     break off (a piece)
        po     appear                pʰo     reveal
        ceʔ    be cooked             cʰeʔ    cook
        sowʔ   be torn, shabby       sʰowʔ   tear
        suʔ    be damp               sʰuʔ    moisten, make damp
        kwe    be split, separated   kʰwe    split, separate

    b.  nasal-initial:
        mjin   be high, tall         N̥mjin  raise, make higher
        niʔ    be submerged, sink    N̥niʔ   submerge, sink

        ne     be loose              N̥ne    loosen (in socket, etc.)
        naʔ    be completely cooked  N̥naʔ   complete cooking

By contrast, in Sukuma (Maddieson 1991), the involved gestures are timed rather differently. Instead of early **voicelessness**, we see late **breathiness**, that is, the simultaneity of voicing and glottal spreading: m̤m̤, n̤n̤, ŋ̤ŋ̤  In (5) are some examples.

(5)  ndɪɪn̤n̤ɔ̂ɔ                ladle
    m̤m̤a̤ala              gazelle
    m̤m̤a̤ala n̤n̤a̤ale       small gazelle
    m̤m̤a̤ajɔ              word

Were voicing not present here, the all-important offset formant transitions would be fully obscured by voicelessness, that is, by the spread glottis. Consequently, when a language possesses this alternative timing pattern, this additional articulatory asymmetry is necessarily present, so that all contrastive information is recoverable. However, this timing configuration comes at an articulatory cost, as breathy phonation requires the larynx to be spread at one end, and simultaneously adducted at the other. This gesture is plausibly more costly that either a fully spread glottis, or a fully approximated glottis

At the auditory level, the sequence of acoustic events, from nasal murmur to breathy nasal to vowel, is perhaps somewhat inferior to the incremental rise in energy found in Burmese. Nonetheless, all contrasts are fully recoverable here as well.

(6)   gross schematic of articulatory, acoustic, and auditory characteristics of late breathiness in nasals:

**articulatory:**
supralaryngeal:   stop            vowel
                  nasal

laryngeal:               abduction
                         approximation   approximation:

**acoustic**
**signal:**

**auditory**
**nerve**
**response:**

**percept:**          n          n̩        a̩        a

How might we formally characterize the Burmese and Sukuma patterns? I choose to take seriously the claim that the phonology may be viewed as a struggle between ease of perception and ease of production (Martinet 1952, Lindblom 1990). Since there is no principled reason why a constraint-based grammar cannot be stated in functionally motivated, extra-linguistic terms, Optimality Theory (Prince and Smolensky 1993, McCarthy and Prince 1993) allows us to formally express this struggle.

The primary goal of a phonology, of course, is to render forms distinct. Thus a primary constraint family values rendering contrasts recoverable. Let's call this family **recover**. A contrastive state that is optimally recoverable is in full accordance with **recover**, while a contrast that is sub-optimally recoverable is not. A fully obliterated cue is in even greater violation of **recover**.

(7)   **recover:**      render contrasts auditorily recoverable
      (no stars)        = cue fully (optimally) recoverable
      *                 = cue sub-optimally recoverable
      **                = cue unrecoverable

In contrast, encoding contrasts should not require excessive effort. Economization of effort is thus valued as well. Consequently, *any* implemented gesture violates what I term **economize**.

(8)    **economize**:    maximize articulatory ease
       (no stars)       = no gesture
       *                = relevant gesture implemented

Finally, to the extent that cues can overlap without obscuring contrastive information, they do overlap. Liberman, Cooper, Shankweiler, and Studdert-Kennedy, and Mattingly (1981), among others, argue that the speech perception mechanism is especially designed for decomposing an informationally complex speech signal, and is less adept at decoding isolated speech sounds. Also, increasing exposure to cues may help convey the contrast. Consequently, parallel production of contrastive information may be optimal, but only, of course, up to the recoverability of contrastive values.

(9)    **overlap**:    cues present in parallel
       (no stars)      = cue present in full parallel with maximally expanded cue
       *               = cue not fully overlapped with maximally expanded cue

So we have three constraint families that operate at the lexical level -- which is, of course, where contrasts are encoded. These can be ranked to characterize attested systems of contrast. However, at the lexical level **recover** is always most highly valued. This is merely a formal way of characterizing the primary function of the phonology, that is, to keep forms distinct. This leaves us with two possible rankings at the lexical level: **recover** >> **economize** >> **overlap**, or **recover** >> **overlap** >> **economize**. Of course, upon morpheme concatenation, allophony and neutralization may result. While I'm not looking at these processes here, they obviously require isolating individual cues for either recovery or economization. For example, in languages with nasal place assimilation, an **economize** constraint **no nasal release before stops** is ranked above the recovery of nasal offset transitions. Without these place cues, only nasal manner may be recovered; independent nasal place is lost (see Jun 1995 for further deatil). Beyond the lexical level then, individual cues may be extracted for particular ranking with respect to one another.

Consider the Burmese pattern, presented in (10). Here the relevant gestures are an oral stop, velic lowering, and glottal spreading, which are implemented in order to achieve particular acoustic results. These are repeated in the second cell, at the top of the **recover** column, which is the highest-ranked constraint. Following in this column are the possible timing patterns which may or may not achieve the optimal result. For Ṇn, onset transitions are pretty much obscured by the glottal noise. However, all other cues are robustly encoded, especially the most important offset transitions. Meanwhile, this timing pattern involves three **economize** violations, as all relevant gestures are implemented. Finally, the glottal noise source, the nasal anti-resonance, which cues place during the steady state murmur, and the low F1 and mid-range energy plateau, which cue the nasal manner, do not fully overlap with each other, and so each incurs a violation here.

Consider next the post-breathy nasal. Here, offset transitions are obscured, but only partially, as offset transitions are breathy, but not voiceless.

Given breathy phonation here, broadband noise is not as readily recoverable as it would be were it fully voiceless, and so this too receives a minor violation. Moving to **economize**, breathy phonation, as stated, requires both voicing and glottal abduction, and thus receives a violation for each. Note that this makes post-breathy nasals more costly than pre-voiceless nasals, at least from an articulatory point of view. Finally, for **overlap**, only broadband noise is in violation, as place and nasal cues overlap with the oral closure. In short, ranking **economize** above **overlap** characterizes the Burmese pattern.

(10)    Nasals and laryngeal abductions in Burmese:

| input | recover | economize | overlap |
|---|---|---|---|
| place | place:<br>offset transitions<br>onset transitions<br>anti-resonance | place:<br>oral closure; release | place:<br>anti-resonance |
| nasal | nasal:<br>low F1; mid-range plateau; | nasal:<br>velic lowering | nasal:<br>low F1; mid-range plate |
| abduction | abduction:<br>broadband noise | abduction:<br>laryngeal opening | abduction:<br>broadband noise |
| ☞ | Nn̥<br>place:<br>offset transitions<br>**onset transitions<br>anti-resonance<br>nasal:<br>low F1; mid-range plateau<br>abduction:<br>broadband noise | Nn̥<br>place:<br>*oral closure; release<br><br>nasal:<br>*velic lowering<br>abduction:<br>*laryngeal opening | Nn̥<br>place:<br>*anti-resonance<br><br>nasal:<br>*low F1; mid-range<br>plateau<br>abduction:<br>*broadband noise |
| | n̥n̥<br>place:<br>*offset transitions<br>onset transitions<br>anti-resonance<br>nasal:<br>low F1; mid-range plateau<br>abduction:<br>*broadband noise | n̥n̥<br>place:<br>*oral closure; release<br><br>nasal:<br>*velic lowering<br>abduction:<br>*laryngeal opening<br>voicing:<br>*approximation | n̥n̥<br>place:<br>anti-resonance<br><br>nasal:<br>low F1; mid-range plate<br>abduction:<br>*broadband noise |

In contrast, Sukuma, in (11), employs the post-breathy nasal variant. This pattern may be characterized by a simple re-ranking of **economize** and **overlap**. Recall that post-breathy nasals have more overlapping of cues than do pre-voiceless nasals, despite their economic disadvantages. Ranking **overlap** above **economize** here thus characterizes the Sukuma pattern.

(11)    Nasals and laryngeal abductions in Sukuma:

| input place | recover | overlap | economize |
|---|---|---|---|
| | place: | place: | place: |
| | offset transitions | anti-resonance | oral closure; release |
| | onset transitions | | |
| | anti-resonance | | |
| nasal | nasal: | nasal: | nasal: |
| | low F1; mid-range plateau | low F1; mid-range plateau | velic lowering |
| abduction | abduction: | abduction: | abduction: |
| | broadband noise | broadband noise | laryngeal opening |
| ☞ | nn̥ | nn̥ | nn̥ |
| | place: | place: | place: |
| | *offset transitions | anti-resonance | *oral closure; release |
| | onset transitions | | |
| | anti-resonance | nasal: | nasal: |
| | nasal: | low F1; mid-range plateau | *velic lowering |
| | low F1; mid-range plateau | abduction: | abduction: |
| | abduction: | *broadband noise | *laryngeal opening |
| | *broadband noise | | voicing: |
| | | | *approximation |
| | N̥n | N̥n | N̥n |
| | place: | place: | place: |
| | offset transitions | *anti-resonance | *oral closure; release |
| | | | |
| | **onset transitions | | |
| | anti-resonance | | |
| | nasal: | nasal: | nasal: |
| | low F1; mid-range plateau | *low F1; mid-range plateau | *velic lowering |
| | abduction: | abduction: | abduction: |
| | broadband noise | *broadband noise | *laryngeal opening |

Finally, let's consider the case of Comaltepec Chinantec (Anderson 1989, Anderson, Martinez, and Pace 1990, Pace 1990, Silverman 1995).    As in Burmese, Chinantec has voiceless nasals with early voicelessness.    Some examples are provided in (12).

(12)    N̥mi:ᴸ            water
        N̥ɲœ:ᴸ           green beans
        N̥ŋajɲʔᴸᴹ        he kills

However, Chinantec also has voiceless nasals in post-vocalic position, stem-finally.  Here, strangely enough, we witness the full simultaneity of all gestures (oral stop, velic lowering, and glottal spreading), with no voicing whatsoever.  This pattern would seem to contradict my claims, as  such a timing configuration fully obscures oral place of articulation.  As it turns out, place of articulation is non-contrastive in such contexts.  Anderson et. al. report that the post-nuclear nasal assimilates in place of articulation to a following consonant. Examples are in (13).

(13)    kaᴸw̥wen?ᴸᴹne?ᴸ              the animal was frightened
        jju:ɲᴴᴸᴴ]aᴴᴸ               this child
        jju:ɲ̥ᴴᴸᴴze?ᴹᴴ           sick child
        p̥im?ᴴ        (<..N? + p)   he is tiny
        jju:m̥ᴴᴸᴴpiŋ?ᴴ         small child
        jju:ɲᴴᴸᴴkʌŋ?ᴹᴴ       big children
        w̥wiŋ?ᴴ               black child
        jju:ɲᴴᴸᴴhaŋ?ᴹᴴ       perverse child
        niᴸḷlejɲ̥ᴹ      (<..N̥ + z̥)  he will tremble
        ?ʌjɲ̥ᴸᴹ       (<..N̥ + z̥)  he pulls (him)

Consequently, either lexical constraint ranking may correctly characterize the post-vocalic voiceless nasals of Chinantec. This is shown in (13), where only nasality and glottal spreading are contrastive. First, glottal noise is present for the duration of the nasal. This, of course, results in the loss of the low F1 and mid-range plateau which normally cues nasality. Instead, nasality is presumably cued by the characteristic frequency of nasally-channeled noise, as opposed to orally channeled noise. Any other phasing pattern would reduce the salience of the glottal noise source, and so recover alone may characterise the realization of voiceless nasality here.

(14)    Nasality and laryngeal abductions in Comaltepec Chinantec:

| input | recover | economize | overlap |
|---|---|---|---|
| nasal | nasal: | nasal: | nasal: |
| | low F1; mid-range plateau | velic lowering | low F1; mid-range plateau |
| abduction | abduction: | abduction: | abduction: |
| | broadband noise | laryngeal opening | broadband noise |
| ☞ | N̥ | N̥ | N̥ |
| | nasal: | nasal: | nasal: |
| | nasally-channeled noise | *velic lowering | nasally-channeled noise |
| | abduction: | abduction: | abduction: |
| | broadband noise | *laryngeal opening | broadband noise |
| | N̥n | N̥n | N̥n |
| | nasal: | nasal: | nasal: |
| | low F1; mid-range plateau | *velic lowering | **low F1; mid-range plateau |
| | abduction: | abduction: | abduction: |
| | broadband noise | *laryngeal opening | *broadband noise |
| | nn̥ | nn̥ | nn̥ |
| | nasal: | nasal: | nasal: |
| | low F1; mid-range plateau | *velic lowering | **low F1; mid-range plateau |
| | abduction: | abduction: | abduction: |
| | broadband noise | *laryngeal opening | *broadband noise |
| | | voicing: | |
| | | *approximation | |

or

| input | recover | overlap | economize |
|---|---|---|---|
| nasal <br><br> abduction | nasal: <br> low F1; mid-range plateau <br> abduction: <br> broadband noise | nasal: <br> low F1; mid-range plateau <br> abduction: <br> broadband noise | nasal: <br> velic lowering <br> abduction: <br> laryngeal opening |
| ☞ | Ṅ <br> nasal: <br> nasally-channeled noise <br> abduction: <br> broadband noise | Ṅ <br> nasal: <br> nasally-channeled noise <br> abduction: <br> broadband noise | Ṅ <br> nasal: <br> *velic lowering <br> abduction: <br> *laryngeal opening |
| | Ṅn <br> nasal: <br> low F1; mid-range plateau <br> abduction: <br> broadband noise | Ṅn <br> nasal: <br> **low F1; mid-range plateau <br> abduction: <br> *broadband noise | Ṅn <br> nasal: <br> *velic lowering <br> abduction: <br> *laryngeal opening |
| | nṇ <br> nasal: <br> low F1; mid-range plateau <br> abduction: <br> broadband noise | nṇ <br> nasal: <br> **low F1; mid-range plateau <br> abduction: <br> *broadband noise | nṇ <br> nasal: <br> *velic lowering <br> abduction: <br> *laryngeal opening <br> voicing: <br> *approximation |

So Chinantec is not contradictory at all. Instead, since place of articulation is non-contrastive here, voicelessness is free to co-occur in full parallel with velic lowering: no contrasts are jeopardized.

In summary then, different timings of articulatory gestures with respect to one another culminate in better or worse percepts. Optimal timing patterns correlate with degree of auditory nerve response: the greater the auditory nerve response, the less marked the pattern, and the lesser the auditory nerve response, the more marked the pattern. For nasals with contrastive laryngeal abductions, pre-voicelessness is optimal, and cross-linguistically more prevalent than its sub-optimal post-breathy counterpart. I conclude that a functional link may be established between the timing of articulatory gestures and their recoverability.

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