THE MECHANICS OF MASTICATION

by Gary S. Tong

Contents

A. Trisegmentals in frameworks

Terms used by Hiiemae and Palmer (2003) are used in this paper. Cycling the food during mastication is **processing**. **Transport 1** refers to the posterior movement of the newly ingested food, and moving food posteriorly toward the deglutition region is called **transport 2.**

General note: it is important to keep in mind that unless otherwise indicated all tongue motions and shaping described occur in an isolated settings. That is, these behaviors take place when the only active agent is tongue, while all other associated parts of the speech mechanism remain neutral.

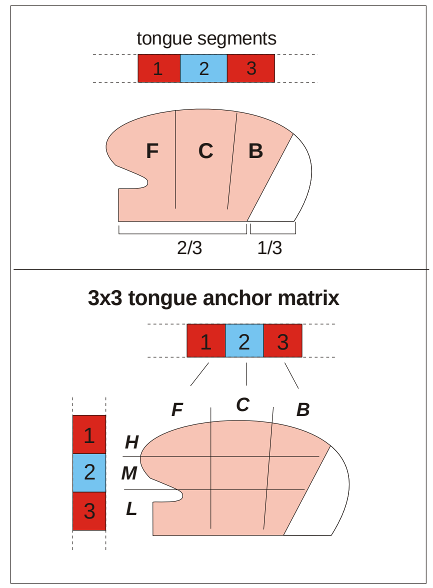
1. **Trisegmental** horizontal and vertical structure forms the 3x3 anchor matrix. Trisegmental **cyclic** action provides the mechanism for both cyclic tongue and jaw movement and tongue shaping in mastication described in Hiiemae and Palmer (2003), as well as the generation of the features of systematic infant babble and syllabic structuring documented by MacNeilage and Davis 1995. This identity underlies the similarity between masticatory and articulative tongue behavior noted by these and other authors. fig. a.

1a. The active tongue anchor here is in the anterior 2/3 part of the tongue (oral part). Its movements are anchored by the posterior 1/2 (pharyngeal) part.

2. The trisegmental structure in and **speech** is essentially the same but performs different functions for reasons including the fact that the jaw is differently anchored in these functions, according to its own particular trisegmental format i.e., placement of its hinge apparatus, (for more on this see Ontology of speech). The jaw is the largest, heaviest and most powerful part of the upper visceral architecture and therefore its particular temporomandibular matrix setting plays a decisive role in framework formation.

3. In the **process** phase of mastication, as termed by Hiiemae and Palmer, lingual anchors generate the various tongue shapes and placements (heaps and valleys) which, in relation to the palate and oral walls and floor, posit and move the food to be repeatedly chewed. These tongue positioning are also the source which generate, when arising in the speech frame, the phonemes d/t, g/k, n, a, i, etc. Fig. a.2. During processing the active central tongue segment is stabilized by the pharyngeal (or posterior 1/3 part of the) tongue.

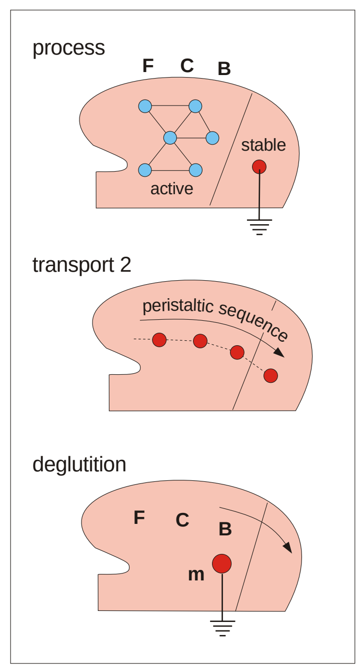
a.1



a.2

a.3

a.4



4. In the **transport 2** phase of mastication the masticated bolus is moved peristaltically posteriorly through the fauces to the tract region of deglutition. fig. a.3.

The anchoring is shared or merged, in sequentially changing proportions, by the front, central and back segment anchors of the oral 2/3 tongue. Entering the **deglutition** phase the stable anchoring passes to the anterior oral 2/3 part and the posterior pharyngeal 1/3 becomes active. fig. a.4.

5. Musculature of tongue segment action

The main muscles of the mastication processing phase are shown in Diagram 1. The intrinsic lingual muscles are indicated only in the central segment action in figure 1.b.

Diagram 1. Musculature of trimeric action in mastication

1a

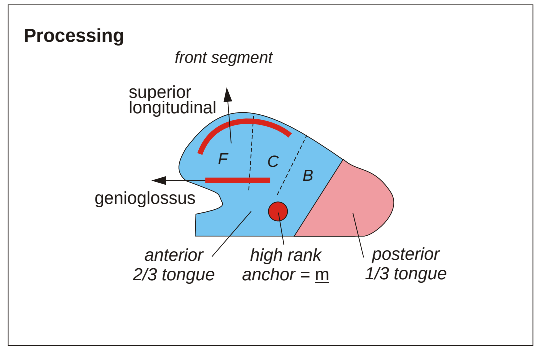


Fig. 1a. In the initial action the **front** segment of the active tongue region creates a **heap** which anteriorly seals of the mastication space and pushes the food inwards. The genioglossus frontally pulls the tongue against the mandible and tenses it, thus heaping it against the palate in coactivity with the superior longitudinal.

1b

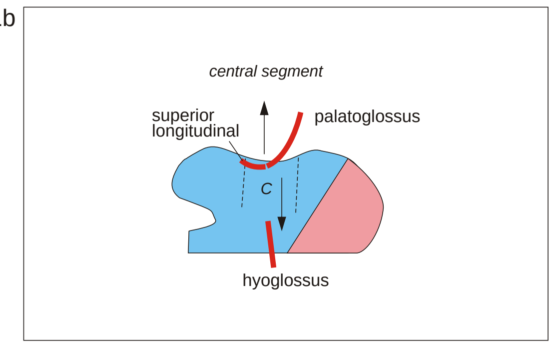


Fig. 1b. The action of the **central** segment **constricts** the tongue and allows the bolus to pass through dorsal and lateral channels. Lingual inward/medial constriction is produced by the intrinsic vertical and transverse muscles which narrow the tongue vertically and laterally.

1c

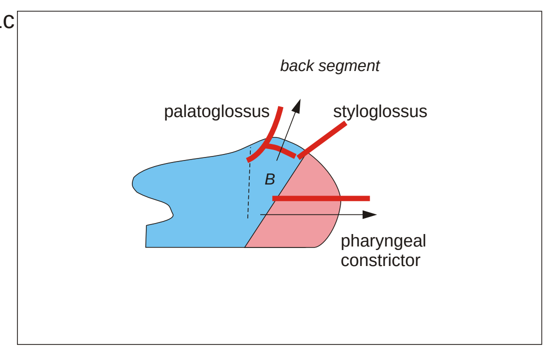


Fig. 1c. The **third** segment forms a **heap** to block passage and then presses the bolus forward to prepare for the next cycle.

Seen as a sequential trisegmental series of closing, opening and again closing the tract, we can interpret it as **peristaltic** action, which has been recognized as the pumping mechanism of suckling (cit.) However, in mastication processing the behavior is not linear, but cyclical and is an example of modified peristalsis, or **metaperistalsis.**

1d

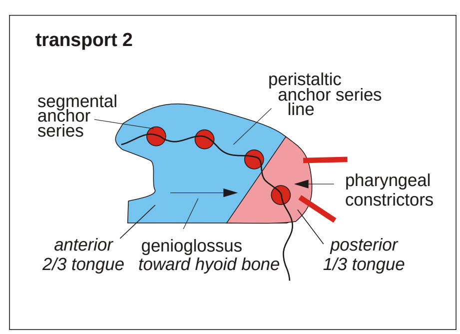


Fig. 1d. shows the muscular map of the **transport 2** phase, where the anchor sequence begins a linear peristaltic action with a frontal segment heap, followed by a central segment valley, and a back segment heap. As food leaves the oral space and enters the deglutition phase, the peristaltic transport continues with serial closure and expansion between the pharyngeal tongue part and the pharyngeal constrictors.

B. The interpretation of lingual aspect of mastication as an anchor-matrix function

We have looked at the anchor-matrix structural mechanics of speech ontology and have established it to be an interaction of complimentary antagonist anchoral trisegments working in monadic coactivity with the mandible. At this point we can interpret the mastication process described by Hiiemae and Palmer as an alternate function of the same structure.

This description is necessarily general because to analyze the complex action of mastication as anchor-matrix behavior requires us to reduce this behavior to a single variable by eliminating all but lingual activity. The coaction of the organs of mastication, the mandible, tongue, velum, etc., creates merged upper visceral frame action which distorts and so masks the anchoral mechanics of the tongue. Tongue action must be isolated by keeping the mandible tonically immobile, and executing only the lingual action of mastication without the presence of food material. Similarly, investigating the effect of jaw action on the tongue the latter must be in a tonic state.

C. The masking factors:

Such isolation is important because the independent shaping and movement of the tongue is controlled by at least three external agencies:

(a) jaw rotation (because the jaw is the most powerful force in the system, and so takes the primary role in coactive and antagonist relations), by

(b) the presence of food material on the surface of thea tongue—bolus on the dorsal tongue causes dorsal arching and bolus on the ventral blade and tip causes ventral arching, while bolus on the sides of the tongue causes axial and transverse constriction on the tongue. fig. c.1.

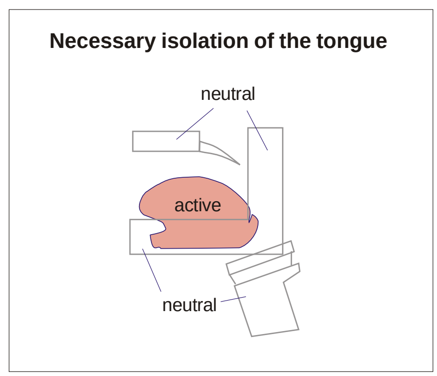
(c) because of laterally asymmetrical twisting movements of the tongue. fig. c.2.

d) various other factors appear when isolation of tongue action is absent, including head and body tilt.

Still another difficulty in full framework masticatory action is the fact that mastication processing contains no discrete components such as are the phonemes in speech, and is a gliding action, rather than syllabic clutch-type anchor change sequence, as is speech.

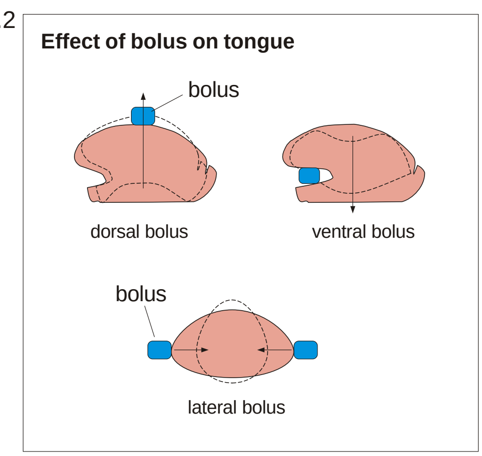
Therefore, describing only the isolated tongue behavior we can analyze tongue shaping and movement as a mapping of lingual masticatory anchors and their envelopes.

c.1



Necessary isolation of the tongue

c.2



Effect of bolus on tongue

D. Structure

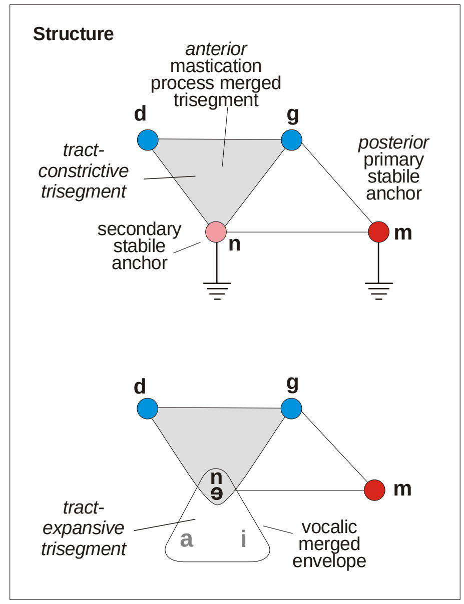
1. The lingual masticatory anchor structure is geometrically composed of four trisegments formed by anchors and lines of forces connecting them. Fig. d.1.

All the units are coactive, and are mutual antagonists or (co-agonists) of one another. The posterior two units are the lingual stabilizing structure for the entire mechanism anchored on m. The two anterior units are a composite dual trisegment performing the cyclic movement of food processing, anchored on n–_. Fig. d.2.

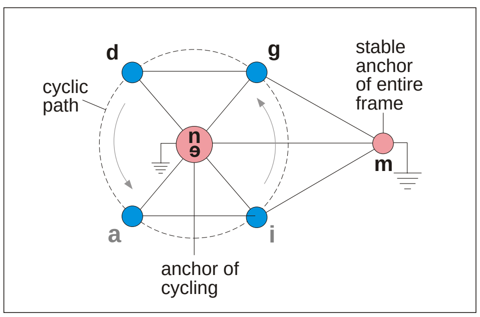
2. In mastication (as in suckling, and unlike in speech), the trisegments a-_-i and t-n-k of the cycling mechanism are not discrete units, but are merged through their combined n+_«central anchor. This composite movement envelope rotates as a single unit. Fig. d.3.

Anchor matrix of mastication process

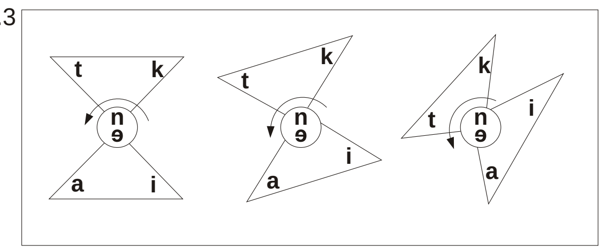
d.2



d.1.



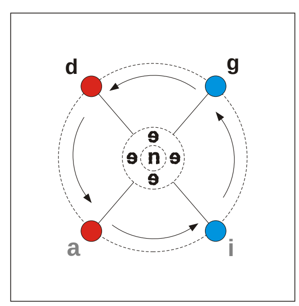
d.3



E. Action: the central anchor of mastication

The consonantal and vocalic trisegments form a single mechanical unit composed of two merged anchor centered envelopes. The two rotate around a common central merged anchor, which is, in turn a merger of the mid-central anchor of each. The n/« merged anchor operates in a unit formed by two concentric envelopes. fig. e.1.

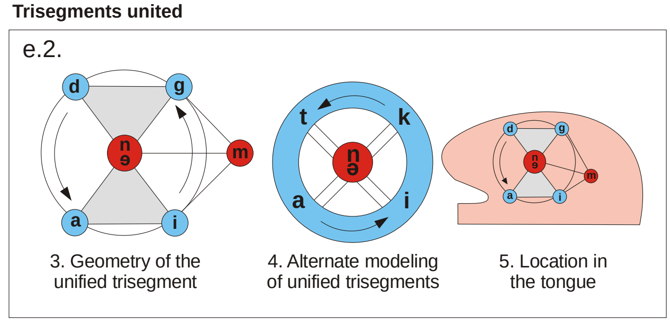
e.1



In terms of tract cross section the n constricts and the ə expands. Thus, the rotation cycle of the anterior trisegment is anchored not only on its mid-central anchor n, but also on its the compensatory antagonist anchor-envelope, which is centered on ə and includes a and i. These two, respectively, germinally consonantal and vocalic envelopes are an antagonist unit pair, each in turn serving to balance or compensate/equalize the tract distortion produced by the other. figs. e.2., e.3., e.4.

Trisegments united

e.2.

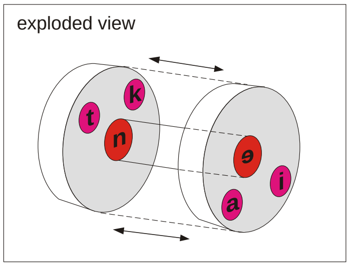


3. Geometry of the unified trisegment

4. Alternate modeling of unified trisegments

5. Location in the tongue

e.3



e. This diagram shows the constrictive and expanding antagonist relationship between n, m and their surrounding coactive tract correcting germinal vowels. The anchor a is coactive with m, while n is coactive with ə. This structure produces the universal /ma/ of early infant speech. fig. e.5.

Cycling in mastication is generated by the coactive antagonist trisegmental pairs already described.

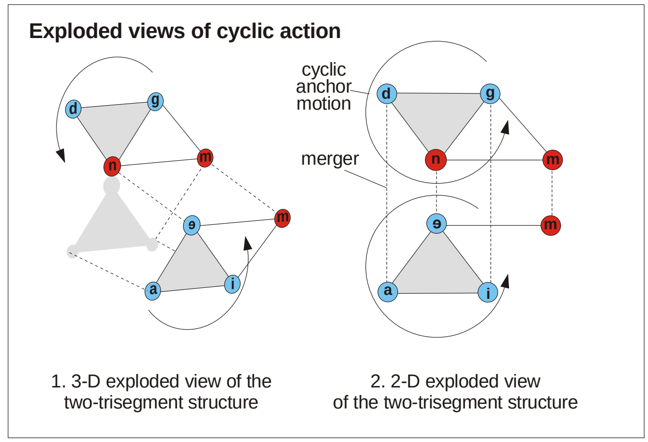
The direction of the cycling is posterior to anterior in general, if starting from the posterior dorsal heap of the tongue, as described by Hiiemae and Palmer. It can be noted that the opposite direction in cycling occurs in suckling and drinking.

The movements of food on the dorsal surface of the tongue serves to transfer material to the dental biting surfaces and to move the chewed material forward. The dorsal trisegment is tract constrictive (or germinal consonantal), activated by the germinal anchors t, n, and k. The ventral trisegment, which moves the food backward, is activated by the a-ə, and i anchors and it is tract expansive (or germinal vocalic).

The cycling of food is achieved through sequential alternation between the upper dorsal and the lower ventral trisegments, the anchors of which move in a glide manner, respectively, anteriorly and posteriorly. It is the bolus of food that actually follows a cyclic path.

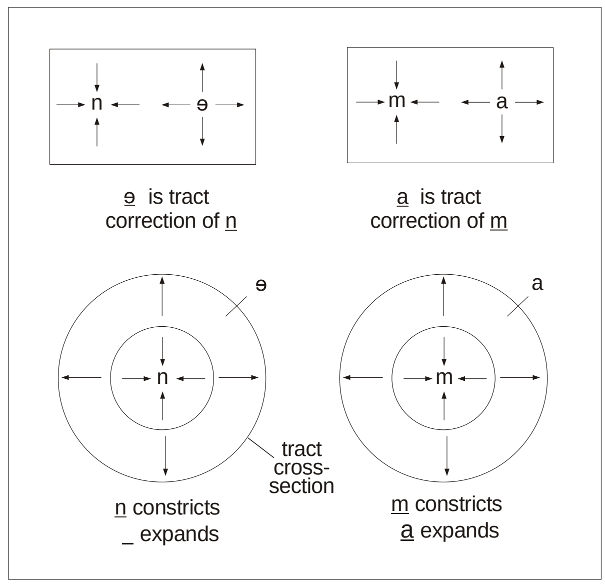
In the initial dorsal phase the active k anchor is transferred to t, then occurs a phase of transition from the dorsal to the ventral trisegmental envelope. Next, the ventral phase consisting of a to i anchor travel transports food backwards until the end of the ventral envelope is reached and then the action primacy is transferred once more to the dorsal envelope phase. fig. e.6.

e.4



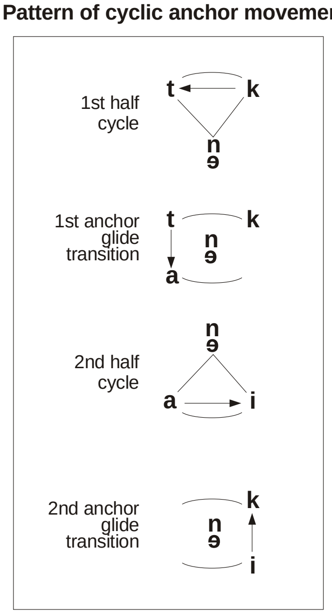
m and n anchor tract corrective vowel associations

e.5



Pattern of cyclic anchor movement

e.6

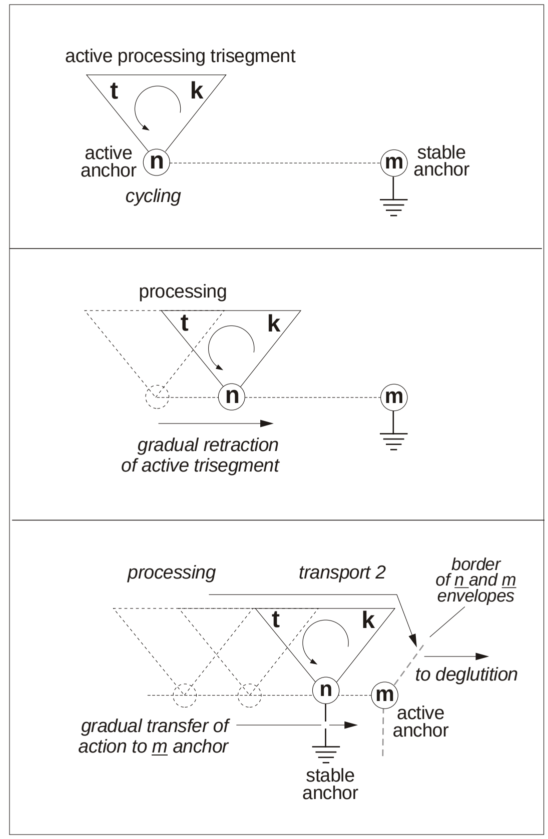


F. Deglutition initiation

As Hiiemae and Palmer reported (cit.), in the mastication process food that is being chewed is repeatedly cycled moving posteriorly in the oral space before once again being re-transported it to the front. The n anchor centering of the action is maintained. But as the food is liquefied the intensity of mandibular and lingual work of chewing action is reduced and at one point the action that gradually moves food posteriorly no longer returns it to the front, but rather, continues moving it posteriorly. fig. f.1.

At such times the action of the cycling trisegment gives way to pre-deglution transport 2, there is an exchange of roles between the n-centered cycle envelope and the m anchor which formerly stabilized it and the former becomes the stabilizing anchor for the m anchor envelope that now becomes active passing the bolus into the pharynx.

f.1

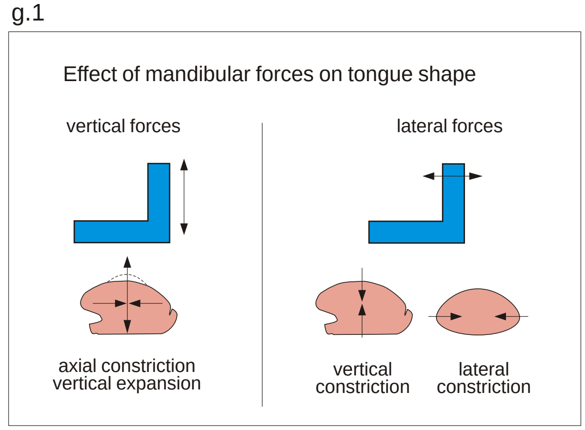


Demo:

If chewing is continuously performed without any food in the mouth, a point in time is reached when swallowing is triggered.

The mechanism behind this is in part metaperistaltic, and in part **glottoregulative.** Th**e** latter is not covered here. (*See G. S. Tong, Foundation of Speech mechanics...*)

g.1



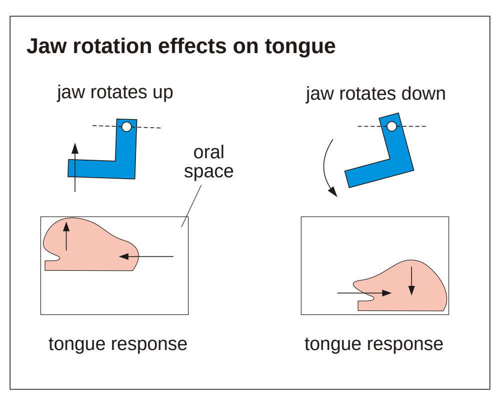
G. Mandible-tongue coactivity

Taking into consideration the mechanics of monadic jaw-tongue unified interaction, it is important to note two facts:

a) when the cranio-mandibular musculature is active, in a non-tonic, dynamically varying energized state, the tongue transversely and vertically contracts in direct proportion to mandibular energy level. fig. g.1.

b) jaw rotation, as has been discussed earlier causes certain tongue relocations and shape changes. (Jaw down—tongue back and k heap; jaw up—tongue forward and t heap.) fig. g.2.

g.2



Taking into account these points, we can sketch the mapping of the anchor envelopes of the masticatory processing cycle.

H. The elision:

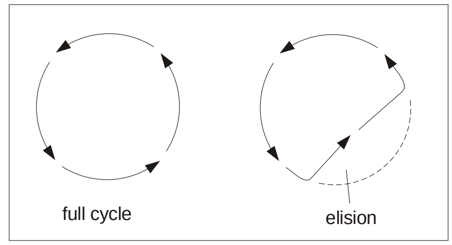
The shape if the tongue anchor matrix changes with the function and energy applied. The modal (lowest energy) state of the UV system is in quiet diaphragmatic respiration. Here the lingual anchor of respiration is active; the 3x3 matrix is passive. In speech, suckling and mastication the 3x3 matrix becomes active and produces characteristic distortions. This is partly from the enlargement of mandibular forces.

In mastication an important distortion appears during the latter part of the ventral half phase of processing: the low back region of the oral space and tongue is compressed toward the center of the matrix, and this effectively cuts out the phase of the i anchor action. An **abbreviation,** or **elision** of the path occurs in anchor movement between a and k, (steps 5 to 1 in **Chart A** (The masticatory cycle)). fig. h.1.

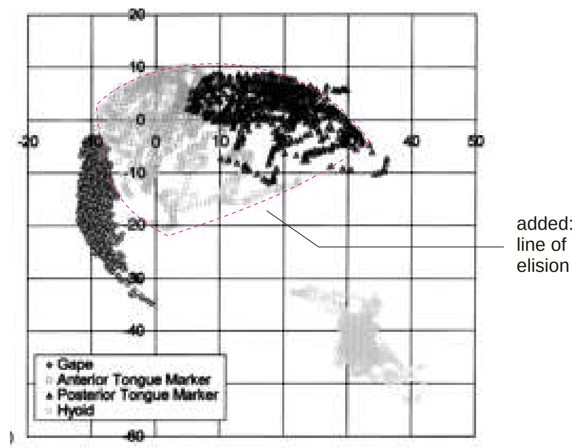
This can be observed through an experiment. If one stops at the appropriate point in the masticating cycle, the various concurrently active germinals, t, k, n, a, and _ can be produced, but i cannot. If the i anchor is generated in this context, there arises a strong bias for triggering **deglutition**.

This back-low truncated shape in the diagram from Hiiemae, et. al., *Hyoid and tongue surface movements in speaking and eating* (2002), which indicates all positions occupied by anterior and posterior tongue markers during a processing cycle apparently **supports** the presence of such **elision**. fig. h.2 .

h.1



h.2



Source: Karen M. Hiiemae, et. al. (2002)

1. The dorsal t-n-k and ventral a-_-i trisegments function as a single merged unit, each centered first on its on mid-central anchor and secondarily, as the merged antagonist pair n/_. An analogue of such hierarchical bistate anchoring occurs in the way a planetary moon orbits around its planet, which in turn orbits its star.

The interchange of dorsal and ventral actions proceeds as a fluid glide.

2. The cyclic motion is generated by alternating exchange of primary agent roles in the antagonist pair. The dorsal tract constrictive phase and the ventral expansive one alternate.

3. Jaw-tongue action is not considered in this isolated tongue map, nevertheless, the positions of the jaw are indicated at the appropriate points in diagram MC. In an actual, non-isolated setting of framework components these mandibular positions are associated with the particular cycle phases.

I. Notes to Chart A: The isolated lingual anchor mechanics of the masticatory process cycle

This diagram depicts the lingual anchor mechanism of the masticatory process as a framework of trisegmental anchor envelopes. It is a map **strictly** of **isolated** tongue behavior with the rest of the framework in a neutral state, so that their influences affecting the tongue and the entire framework are minimized. The positions of the jaw, which are also shown serve only as reference.

1. The steps in the masticatory processing cycle in Chart A:

1. The steps in the masticatory process cycle in Chart MC :

1. The k-heap in dorsal trisegment primacy starts forward dorsal transport of bolus, which is in the dorsal space.

2. Midway point in dorsal transport.

3. Anterior t heap gates (blocks) the bolus movement.

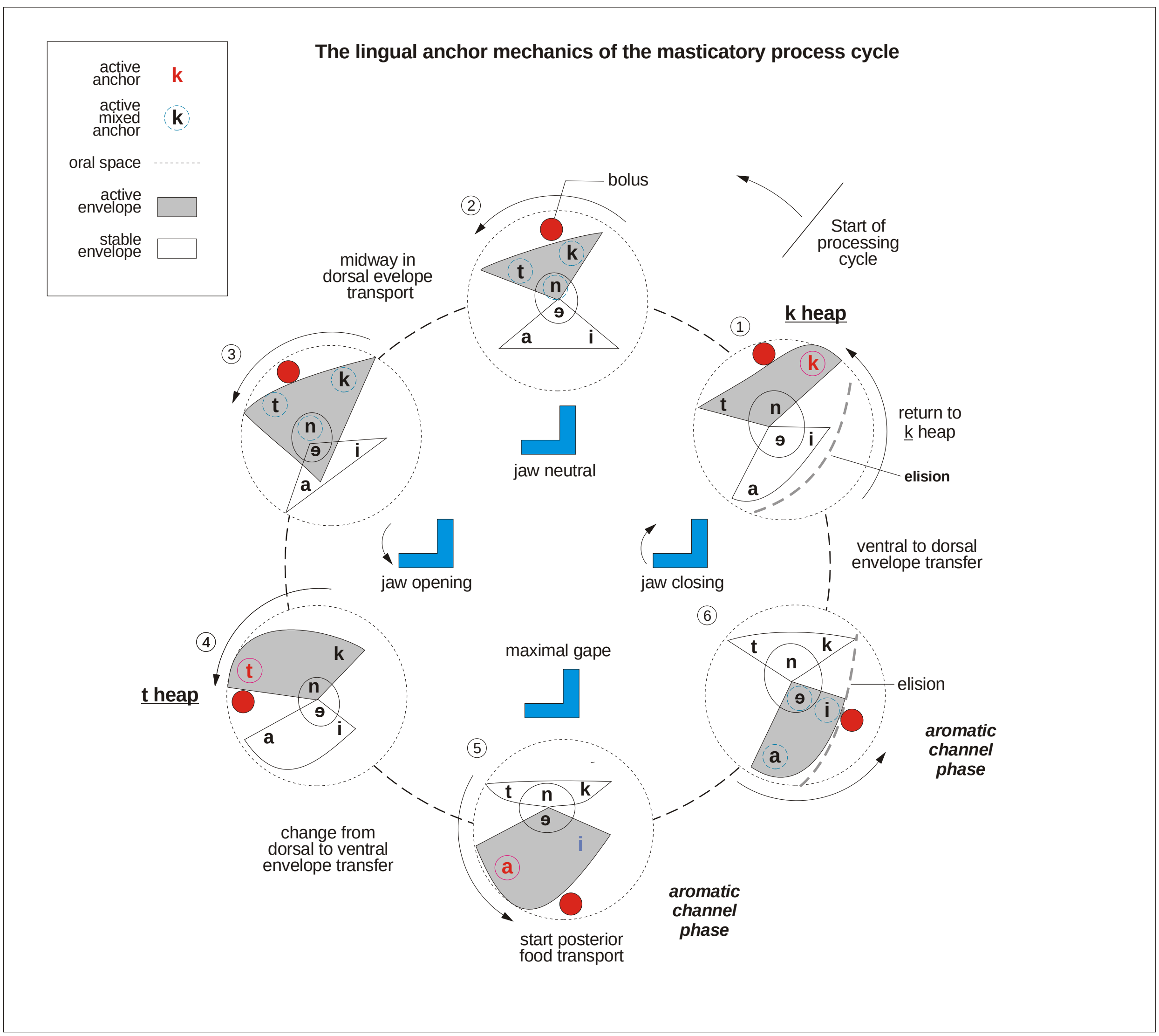
4. Transferring of anchor/envelope primacy between the two trisegments. The bolus is about to enter the ventral space.

5. Ventral trisegment primacy (tract compensation) opens the channels inferior and lateral to the tongue. A germinal a heap posteriorly moves the bolus in the ventral space.

6. The envelope space of the germinal _ is elided, see above 8. Elision.

7. Transfer of primacy once again, from ventral to dorsal, returning to the k heap position. The new cycle begins.

Chart A - The masticatory cycle)



J. Retronasal aroma perception

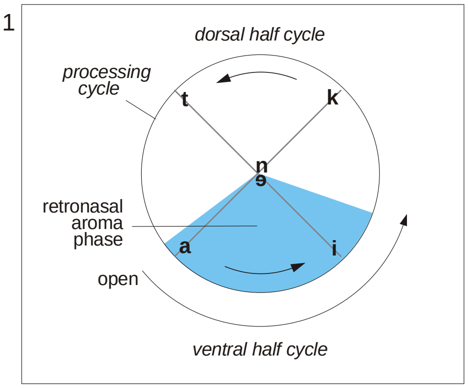
Olfactory perception of food **aroma** is an essential part of food processing and it is enabled through the specific phases of the cyclic movement of the n/_ envelope. The germinal stops that generate the front and back gate heaps of the tongue are constrictive, and since constriction in one valve of the UV causes the constriction of the remaining valves, the envelopes of these germinals will also close the velar and nasal air channels. However, the a-_-i envelope, which is the tract expanding respiratory compensatory antagonist envelope of the t-n-k trisegment, enlarges the tract, including that of the velar and nasal regions, and thus allows the passage aromatic air. This occurs during the phases when the ventral trisegment is primary agent and air is expired. figs. j.1. and j.2.

During **deglutition** the valves are once more closed, but immediately after the bolus enter the esophagus the m/a envelope expands the velo-nasal tract to receive the residual air that has filled the pharynx during deglutitional compression. At that time deglutition is followed by expiration and the aroma of that particular swallowing is sensed once more for a final time. Inspiration never occurs on completion of deglutition. This is the moment when people approving of food typically generate the /m/ sound.

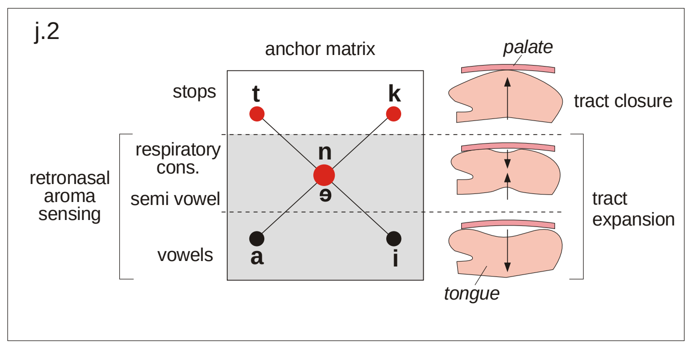
Thus, it is during the backward cycling and transport of the processed food that the aromatic components of food are perceived.

Demonstration: in the masticatory mode, but with no food in mouth, slowly and carefully expire nasally. Note that the tongue and oral space takes on the a-_-i configuration.

j.1



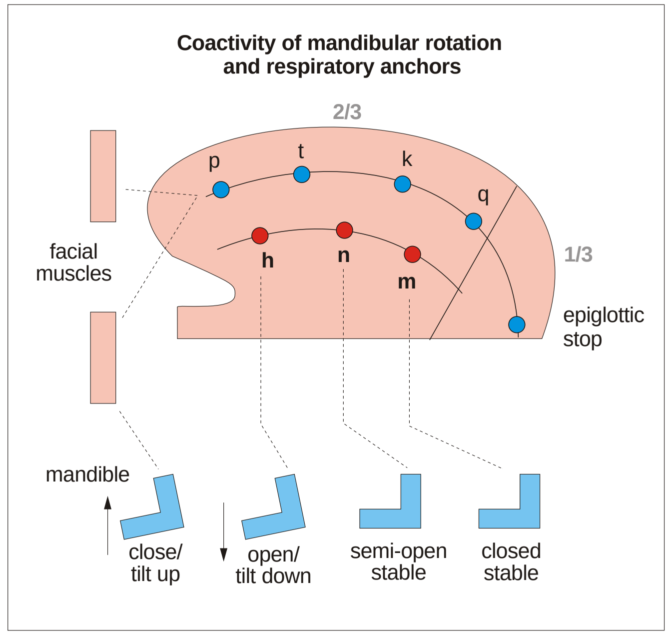
j.2



K. Functions of the lingual anchor m

1. Lingual anchor matrix: its various roles in of mastication and respiration

k.1



The diagram illustrates the association of jaw rotation with respiratory germinal (or tract maintenance) anchors. With the m anchor, serving nasal respiration with closed mouth, the jaw is locked, while n, also anchoring nasal respiration, the jaw and lips (coactive with associated facial muscles), may or may not be closed, locked in a neutral pose, neither closed or opened with force,while the jaw is in large part held up by the tongue and its associated subframe. The tongue forms the oral gate that blocks oral air flow. This is also the subframe of active olfaction where the mouth is closed and embedded in the frame is the anchor of phonemic /m/. fig. k.1.

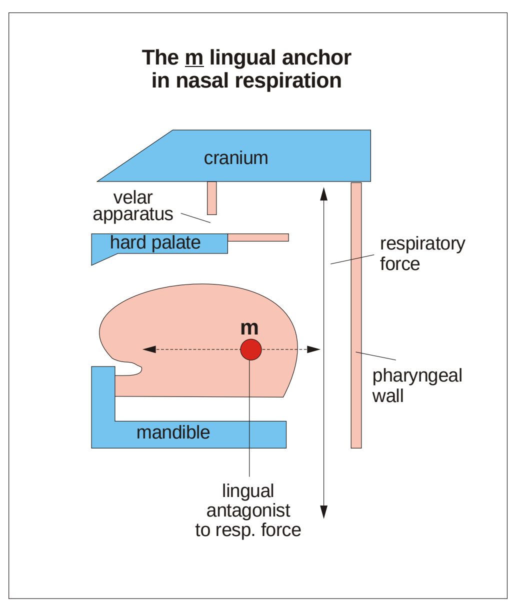
With the h anchor active the mandible descends and oral respiration ensues. (On total forceful jaw down rotation the entire UV framework locks, and airflow is blocked.) On elevation of the mandible and closure of the lips the m anchor once more becomes active but now merging with the p and epiglottic anchors, it also causes labial closure. (Holding the mandible open during m-anchored nasal respiration is possible, but not in producing /m/ within the speech framework.)

Note: The role of the lingual respiratory anchor m in the various subframes.

Since m is the primary anchor of low energy nasal respiration, it appears in all UV function frameworks except in oral respiratory modes, where it remains embedded in the superimposed h anchoral subframe.

2. The lingual m anchor in nasal respiration mode

k.2



The active respiratory (pulmonic) force direction is **vertical** as it passes from the trachea into the pharyngeal tract and then turns 90 degrees entering the nasal passage. In this situation, the tongue is an antagonist to the pulmonic force distorting it and it maintains appropriate lingual shape and position, and is coacting with the entire nasal respiratory framework. The lingual anchor is in respiration is m. fig. k.2.

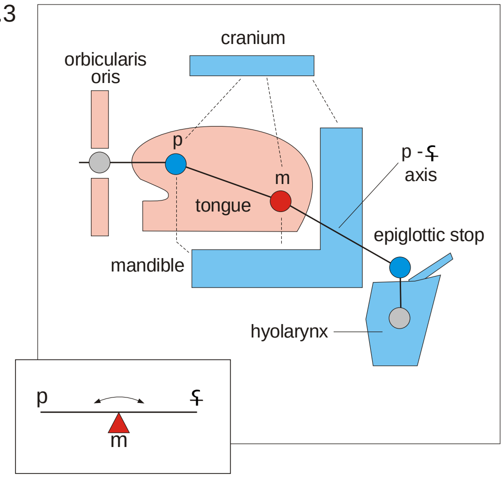
3. The lingual m anchor in the p-epiglottic stop tract

The p-ʢ tract is the section of the UV system between the lingual anchors of p and the epiglottic stop (ʢ).

Here the m lingual anchor balances the two extreme lingual anchors of the UV tract, p and the epiglottic stop (ʢ). The surrounding larger framework enclosing the lingual one is composed of the cranium, the oral sphincter, the mandible and the hyolarynx. Further out from the central m anchor, on opposite sides are the anchors of the lips closure (orbicularis oris) and the hyolarynx. fig. k.3.

p-epiglottic stop tract

k.3



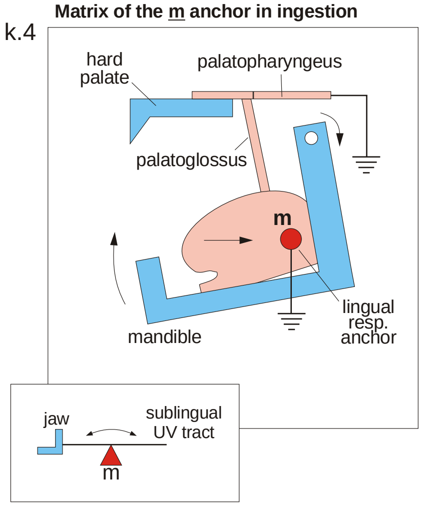
4. The lingual m anchor in food ingestion

Ingestion is the introduction of food into the oral cavity.

In this structure the m anchor balances the tongue against the downward rotating jaw and, through the velar and pharyngeal constrictors, against the hard palate, cranium, and sublingual tract. This balancing force also closes the velopharyngeal and epiglottic valves. Normally m is the lingual anchor of nasal respiration, the active overriding primary force of the rotating jaw assigns it into a different role. The lips and the hyolarynx are also part of this framework: at the close of ingestion the lips and the glottis close the tract. fig. k.4.

Matrix of the m anchor in ingestion

k.4

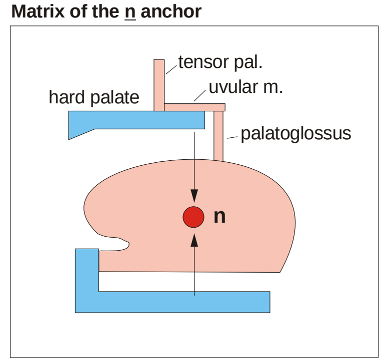


5. The matrix of the n lingual anchor

The n/ə anchor stabilizes the entire process matrix. The n anchor constricts the tongue medially, pulling at its connections with the velum and the mandible, which also constricts the tract in response. The corrective velar response of the ə anchor simultaneously opens the tensor palatini gate and the lingual gate so that both food and aroma are allowed to pass through the tract. During the dorsal t-k phase all UV valves are closed. fig. k.5.

Matrix of the n anchor

k.5



6. The m-anchor in the matrix of the masticatory

Here m anchors the active t-n-k trisegment of mastication. Fig. a0. And in simultaneous coaction the m also anchors of the closing coaction of the jaw and p. As its role changes according to the phase, the m fluidly alters the force map. fig. k.6.

a. The framework of the mastication process is a subframework within the full feeding tract frame. Its stable anchor is the germinal m. fig. k.7.

The surrounding antagonist, or tract correction adjuster of m, is the germinal a. Its associated stop is p and these two coact in mandible and lip closure. The antagonist of the stable m anchor is the active trisegmental unit of t-n-k. fig. k.8.

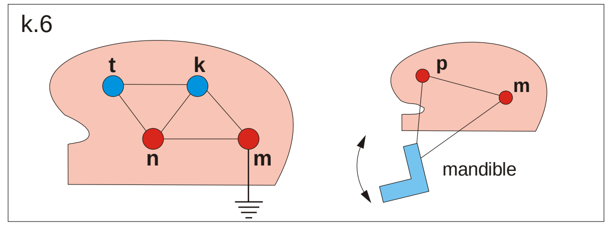
Lip closure is tract corrector to p: it generates expansion of the respiratory tract.

b. m and p form a separate trisegmental unit (of higher hierarchical rank), over which the mastication subframe is temporarily superimposed at the close of ingestion. fig. k.9.

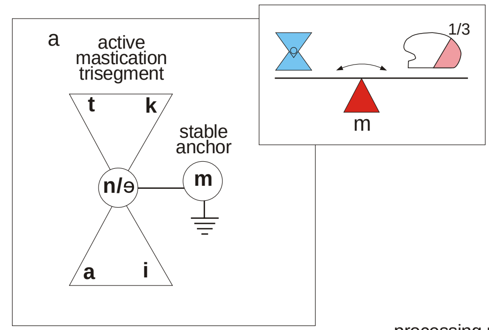
c. The mastication subframe is composed of the merged consonantal t-n-k and the vocalic a-ə-i trisegments, with the stabilizer anchor m. fig. k.10.

d. The masticatory subframe is in turn the stabilizer anchor for an active m, when within its tract region the latter anchor takes part in propulsion of food toward the deglution triggering region. fig. k.11.

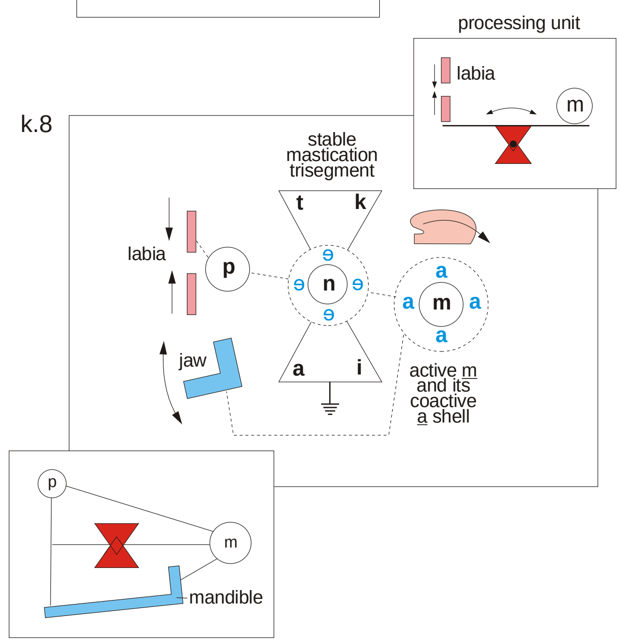
The lingual anchor matrix of mastication process



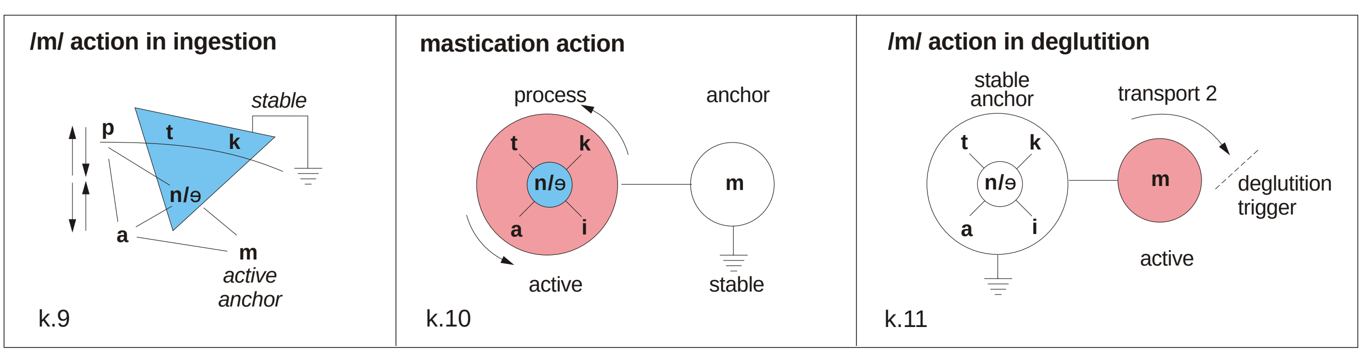
k.7



k.8



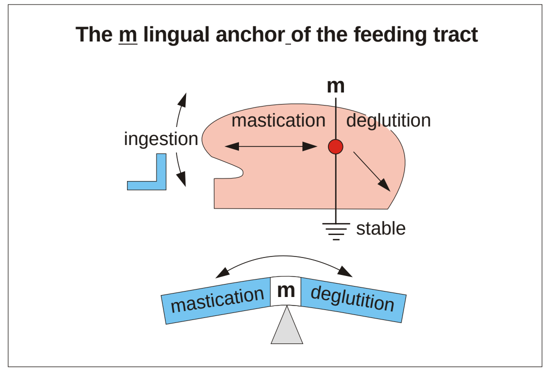
The /m/ anchor framework in feeding



7. The m lingual anchor of the full feeding

The lingual anchor m serves to stabilize and balance the entire sequence of feeding function, including ingestion, mastication and deglutition. Both the structural lingual stability and the requirement of respiration are served by the m anchoring. In addition, both the structural stability of the tongue complex and that of the respiratory frame are simultaneously met by the m anchoring. The functions of the two frames are merged. fig. k.12.

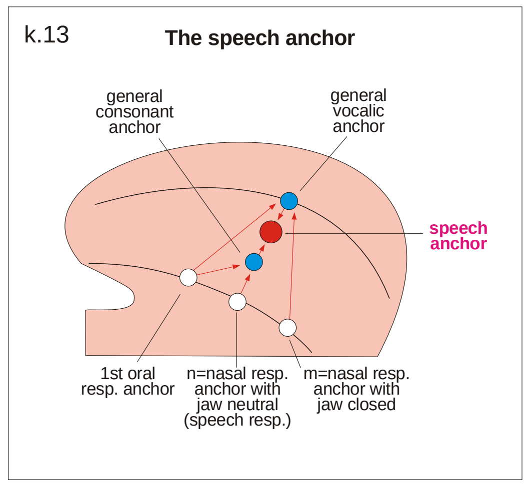
k.12



8. The m lingual anchor in the speech

The oral speech framework is more open than that of respiration, suckling and mastication and is a more complex and higher energy function. The working speech anchor is formed by the merger of the general vocalic and general consonantal anchors, which in turn are produced by the merger of the 1st oral respiratory anchor, respectively, with the n and the m nasal respiratory anchors. (The first oral respiratory anchor is a merger of the n and the h anchors.)

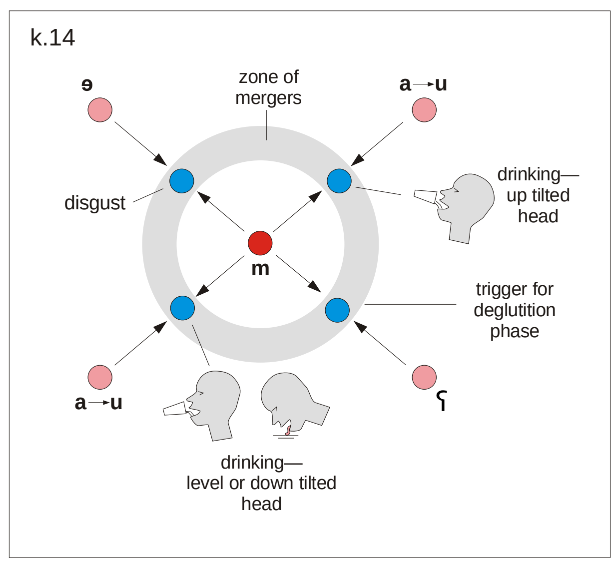
It may be asked how the m anchor occupied in both respiration, a vocalic merger plus an additional merger with the consonantal anchor can also serve as the anchor of the phoneme m. The answer is that an anchor can be reproduced, or re-superimposed, a number of times. (See Superimposition in Outline of structure.)In producing the syllable /mom/, for instance, a temporary composite subframe is generated, which is the underlying vocalic syllable frame of a merged with the superimposed initial m, then after the vowel is concluded the second (final) m is once more superimposed. This is source of the great variety of phonemic articulation. fig. k.13.



f. The m anchor in other functional

The germinal m, constantly present in other UV functions as the anchor of nasal respiration, enters into various mergers with appropriate tract corrective anchors. fig. k.14.

Coactive with a sequence moving from the high back a to high back u anchors, m serves as the lingual anchor of **drinking** with the head posteriorly tilted, while with the low front a to u sequence it serves in **drinking** with a level or forward tilted head. The propulsive force is provided by the t-n-k lingual trisegment and jaw movement, as in mastication. The sound typically producible when drinking with back tilted head is /g/, generated by the cyclically recurring (voiced) k gate closure. The frontal t/d closure found in mastication is repressed in drinking, due to jaw opening.



Merged with _, the m anchor stabilizes the subframe of food **rejection**, or **disgust** with taste.

When m merges with the epiglottic stop (ʕ) anchor, it acts as the trigger of the deglutition function.

As evidence the following can be offered:

a. Either execute the above described merger of lingual anchors, tilting the head when appropriate, and then note whether the resulting anchors in fact function as stated,

b. or while performing any of these behaviors, stop in mid action, hold the muscular map and then slowly relax the map to a minimal tension, till the map becomes relatively stable. Now note that what phonemes are spontaneously producible from the map.

Miscellaneous notes:

1. The tnk/dng mastication phase cycle occurs during processing of hard foods, which need dental chewing.
2. The i mastication phase cycle occurs with soft foods! where bolus is pressed and mixed, but is not dentally chewed.
3. In normal average mastication both cycles are present, in proportion to degree of completion of processing food of mixed hardness.

4. In suckling the a-ə-i cycle is active, and d-n-g anchors are stable, rhythmically palatally pressed by mandibular action.

References

Bosma J.F. et. al., *Ultrasound demonstration of tongue motions during suckle feeding*, Dev. Med. Child Neurol., 1990 Mar;32(3):223-9.

Karen M. Hiiemae and Jeffrey B. Palmer, *Tongue movements in feeding and speech*,
Crit Rev Oral Biol Med, 14(6):413-429 (2003)

Karen M. Hiiemae, et. al., *Hyoid and tongue surface movements in speaking and eating*, Archives of Oral Biology 47 (2002) 1127

Barbara L. Davis and Peter F. MacNeilage, *The articulatory basis of babbling*, Journal of Speech and Hearing Research Vol.38 1199-1211 December 1995.

Peter F. MacNeilage, *The Frame/Content theory of evolution of speech production*, Behavioral and Brain Sciences, l998, 21, 499-546.

Anthony J. Seikel, Ph.D., Douglas W. King, Ph.D., David G. Drumright, *Anatomy & Physiology for Speech and Language*, Singular, 1977. (1st edition).

A. J. Sokoloff, *Activity of tongue muscles during respiration: it takes a village?*, J Appl Physiol 96: 438-439, 2004.)

Voloschin L. M., et al., *A new tool for measuring the suckling stimulus during breastfeeding in humans:the orokinetogram and the Fourier series*, Journal of reproduction and fertility 1998, vol. 114, no2, pp. 219-224

Zoppou C., Barry S. I., and Mercer G. N., *Dynamics of human milk extraction: a comparative study of breast feeding and breast pumping*, Bull Math Biol. 1997 Sep;59(5):953-73.