Quantal biomechanical effects in speech postures of the lips

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ICPhS 2019
August 9, 2019
Why does labial typology look the way it does?

**General observation:** Languages tend to use different lip shapes for different degrees of labial constriction.

**This presentation:** We suggest that this is in part due to quantal biomechanical properties of these shapes that allow for robust, feed-forward control.

Let’s start by looking at the 451 languages in the UCLA Phonological Segment Inventory Database (UPSID; Maddieson 1984, Maddieson and Precoda 1990)
UPSID labial typology (451 languages)

Though not without exceptions, there’s a clear generalization:

- **Labial stops**: 99.8% bilabial (0.2% labiodental)
- **Labial fricatives**: 71% labiodental (29% bilabial)
- **Labial approximants**: 98% rounded (2% labiodental)
Why should this be the case?

A language could produce different degrees of constriction by **varying the activation of a single labial movement**:

- Labial stop: \([p]\)
- Labial fricative: \([p̂]\)
- Labial approximant: \([p̊]\)

Languages don’t do this!
Why these mechanisms?

Mechanisms built for a task will be robust to noisy, everyday conditions (e.g., Loeb 2012)

- Allow a large margin of error
- Optimize for feed-forward function (e.g., Perkell 2012; Guenther 2016)

Speech mechanisms with such properties are associated with the term quantal (e.g., Stevens 1972; Stevens 1989; Stevens and Keyser 2010)

- Large variation in input → little response in output
Past work on quantal biomechanics

Limited discussion of quantal biomechanical effects
(e.g., Fujimura and Kakita 1979; Fujimura 1989; Perkell et al. 2004; Perkell 2012)

Simulation studies have demonstrated quantal effects in

- The soft palate (Gick et al. 2014; Anderson et al. 2019)
- The larynx (Moisik and Gick 2017)
- Lip rounding with variations in muscle stiffness (Nazari et al. 2011)

Not all sets of muscle activations exhibit quantality!
(Gick et al. 2014; Moisik and Gick 2017)
The current study

Tests for quantal effects in the three canonical lip postures using a 3D finite-element face model.

- Biomechanical modeling platform Artisynth (e.g., Stavness et al. 2012)
- Simulates biomechanics and actions of fixed groupings of muscles
- Passive tissue mechanics, active muscle stress and intrinsic stiffness, volume preservation, gravity
Assumptions & Predictions

Assumptions

● Speech movements are generated by functionally independent groupings of muscles that activate in fixed proportion (modules) (e.g., Bernstein 1967; Ting et al. 2015)

● Selected in part based on intrinsic quantal biomechanical robustness
Assumptions & Predictions

Predictions

Canonical lip modules will be

1. Robust across a wide range of activation levels
2. Robust to interference from surrounding muscles
Simulation 1: Robustness to varying activation

- Defined muscle groupings based on known muscle involvements (Lightoller 1925; Stavness et al. 2013)

- Each posture uses a different set of muscles (sometimes overlapping)

- No “right” choice: many inputs will contain the necessary mechanic (e.g., Loeb 2012)
Simulation 1: Robustness to varying activation

- Activated muscle groupings up to maximum stresses
- Measured opening size at different activation levels
Simulation 1: Results

Non-linearities occur as predicted!

- Grey boxes: areas where 95% of distance to maximum closure has been covered
Simulation 1: Results

Takeaway

All three speech postures are robust to variation in activation levels of relevant muscle groups.
Simulation 2: Robustness to surrounding muscles

**Question:** Are these postures robust to interference from surrounding muscles?

Focus on **approximant** (activating OOP)

- No contact, easier to see variable effects

**Two types** of simulations:

1. Is lip constriction stable when there is surrounding muscle noise?
2. How does degree of OOP activation affect this stability?
Simulation 2: Type 1

Sampled OOP activation $\sim U(0\%, 100\%)$

1. Without activation of surrounding muscles (same as Sim. 1)

2. With activation of surrounding muscles $\sim U(0\%, 10\%)$
Simulation 2: Type 1 Results

No surrounding noise

Surrounding noise
Simulation 2: Type 2

Sampled OOP activation from **two distributions**

1. **Low activation** $\sim N(10\%; 10\%)$

2. **High activation** $\sim N(80\%; 10\%)$

Other muscles $\sim U(0\%, 10\%)$
Simulation 2: Type 2 Results
Simulation 2: Type 2 Results
Simulation 2: Type 2 Results

Higher OOP activation reduces interference from surrounding muscles

- Variability in high activation region is significantly lower

The high activation region falls in the quantal region in Simulation 1!

- Same region is robust to both intrinsic and extrinsic activation noise
Discussion

Why don’t we see labial inventories that look like [p], [p̊], [p̊̊]?

- The regions in which friction and approximation are achievable using this configuration are biomechanically unstable.

The sets of muscles associated with the three canonical lip postures are:

1. Robust to intrinsic activation noise (Simulation 1)
2. Robust to extrinsic noise from surrounding muscles (Simulation 2)
Discussion

Suggests a biomechanical contribution to typological distribution of labial sounds.

What about bilabial fricatives?

- The mechanism for bilabial fricative constriction may not be the same as for bilabial stop closure (e.g., lip compression; Okada 1991)
- Serves as competing alternative to labiodental fricatives
Discussion

Bears on theories of speech organization and motor control

- Degree of constriction and involved articulators are *not independent parameters*!

- Primitive units of organization are *modular muscle groupings* that *activate in a fixed proportion* to achieve a *particular functional goal* (e.g., Bernstein 1967; Safavynia and Ting 2013; Gick and Stavness 2013; Ting et al. 2015)

Understanding these structures provides explanatory power for linguistic phenomena.
Thank you!

The authors acknowledge funding from NIH Grant DC-002717, NSERC RGPIN-2015-05099, and a SSHRC Doctoral Award to C. Mayer.
References I


References II


References III


References IV


Quantal regions

A region of a function in which large variation (error) in one dimension effects little response in some other (task) dimension

- Solid line: strongly quantal
- Dashed line: fairly quantal
- Dotted line: not quantal
Simulation 1 & 2: Muscle sets and ranges

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<th>OOPi</th>
<th>OOMs</th>
<th>OOMi</th>
<th>MENT</th>
<th>RIS</th>
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**Table 1:** Maximum muscle stress (kPA) used for the three lip constrictions.

**Simulation 2** noise muscles: above muscles, plus depressor anguli oris, buccinator, depressor labii inferior, levator anguli oris, zygomaticus

**OOMs/i:** superior/inferior marginal orbicularis oris  
**OOPs/i:** superior/inferior peripheral orbicularis oris  
**MENT:** mentalis  
**RIS:** risorius  
**LLSAN:** levator labii superioris alaeque nasi  
**LLS:** levator labii superioris
Simulation 1: Q-scores

The **Q-score** of a function quantifies quantality (Moisik and Gick 2017):

- Compares first derivative in earlier and later ranges
- Based on heuristics in Moisik & Gick (2017):
  - Stop is *strongly quantal*
  - Fricative and approximant are *moderately quantal*
Simulation 1 & 2: Calculating opening size

**Simulation 1:** Count pixels in coronal images, convert to mm\(^2\)
- Labiodental calculated between lower lip and upper teeth
- Other sounds between lower lip and upper lip

**Simulation 2:** Calculate minimum opening size along a series of cutting planes
- Necessary because of large number of simulations

Probabilistic sampling of inputs done using the BatchSim tool