Abstract
This paper shows how an articulatory model, able to produce acoustic signals from articulatory motion, can learn to speak, i.e. coordinate its movements in such a way that it utters meaningful sequences of sounds belonging to a given language. This complex learning procedure is accomplished in four major steps: (a) a babbling phase, where the device builds up a model of the forward transforms, i.e. the articulatory-to-audiovisual mapping; (b) an imitation stage, where it tries to reproduce a limited set of sound sequences produced by a distal “teacher”; (c) a “shaping” stage, where phonemes are associated with the most efficient sensori-motor representation; and finally, (d) a “rhythmic” phase, where it learns the appropriate coordination of the activations of these sensori-motor targets.

1. Introduction
The generation of synthetic speech from articulatory movements faces two main challenges: (a) the classical problem of the generation of a continuous flow of command parameters from a discrete sequence of symbols and (b) the adequate use of the degrees of freedom in excess of the articulatory-to-acoustic transform. An efficient solution is to separate planning from execution (cf. Fig. 1): the planning parametrises the linguistic task in adequate representation spaces whereas the execution converts these distal specifications into actual commands for the articulatory synthesizer.

Concurrent to the Task Dynamics approach [13], where distal objects of speech production are supposed to be constrictions in the vocal tract, our current approach make use of those distal representation spaces best adapted to the sound to be uttered: exteroceptive, haptic or proprioceptive information are collected in course of the movement so as that the planning process could make use of the most appropriate feedbacks.

2. Emergence of representations
2.1. The control model
The control model used here has been developed within the Speech Maps project [12]. The so-called articulotron is based on the following principles:

- a positional coding of targets: each sensori-motor region associated with a percept is modelled as an attractor which generates in all speech representation spaces a force field which attracts the current frame towards that region.
- a back-projection of these force fields to the motor space of the plant: the controller implements a pseudo-inversion of all proximal-to-distal Jacobians.
- a composite and superpositional control: each sensori-motor target has an emergence function which can overlap those of adjacent targets. Force fields generated in each representation space are thus weighted and added, then back-projected. These motor force fields are then combined and integrated to determine the actual articulatory movement.

When computed in different representation spaces, back-projected fields may contradict each other. The strategy for resolution of conflicts is essential in motor control and we describe in section 5 our current strategy.

3. Audiovisual inversion
The simplest way to give our speech robot, the “articulotron” 2, the gift of speech is to imitate an audiovisual speech synthesizer via a global inversion. The audiovisual characterisation is delivered by an audiovisual “perceptron” 2. This perceptron may deliver a continuous distal specification as in [13] or sample these audiovisual specifications at salient events as proposed by [16].

We adopted the distal-to-proximal inversion proposed by Jordan [11] where the inverse Jacobian of the forward -

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Figure 2: The two first discriminant spaces. From left to right: acoustic, geometric and articulatory spaces.

articulatory-to-audiovisual transform - is used to convert the distal gradient into a proximal one. The proximal gradient is augmented by a smoothness criterion with a forgetting factor. This smoothness favours solutions which minimise jerk. Thus starting from an initial articulatory configuration, articulatory movements progressively converge towards gestures producing the appropriate exteroceptive information with minimal jerk.

3.1. The plant - proximal parameters
The plant has been elaborated using a database of 1600 X-rays obtained from a reference subject [2]. Eight degrees-of-freedom [8] will be used here. The model intrinsically couples jaw rotation and translation, controls upper and lower lip relative position and protrusion, controls larynx and velum position and has four degrees-of-freedom for the tongue mid-sagittal section.

3.2. Distal characterisation
The perceptron delivers here continuous formant and lip area trajectories of the sounds emitted by some distal teacher. In the following, the distal teacher is the same subject who was X-rayed to build the articulatory model. This avoids normalisation procedures which are beyond the scope of this paper.

3.3. Forward modelling
The forward proximal-to-distal transform is learned in the babbling phase. This many-to-one transform from eight articulatory parameters to the first four formants and area of the lips is modelled by a polynomial interpolator. The four formants were estimated from the area functions delivered by the plant using [1]. The order for each interpolator was set experimentally to 4. The interpolator was initially estimated using the set of 1600 configurations of the X-ray database augmented by a random generation of the articulatory parameters. The actual database has 17368 frames.

3.4. The corpus
Our French speaker pronounced two sets of $V_1CV_2$ where $C$ is a voiced plosive: (a) with a symmetric context ($V_1=V_2$) with the ten French vowels and (b) an asymmetric context where $V_1$ and $V_2$ are one of the extreme vowels /a,i,u,y/. The set of audiovisual stimuli which will enable our control model to build internal representation of speech sounds consists thus of 78 stimuli, comprising 78 exemplars of voiced plosives and 156 vowels.

3.5. Distal-to-proximal inversion
The inversion procedure is done for the whole set of speech items described above. Inversion results have been assessed in two cases: (a) a static case where prototypic articulatory vocalic configurations obtained by a gradient descent towards speaker-specific prototypic acoustic configurations are compared with both the articulatory targets extracted from the X-ray database and well-known structural constraints [7]; (b) kinematic inversion where results on the inversion of VCV sequences are compared with the X-ray data at well-defined time landmarks. The results published in [7, 5, 3] show that such simple global optimisation techniques are able to recover accurate and reliable articulatory movements.

4. Building sensori-motor spaces
Once inversion of the whole set of items has been successfully performed, the imitation stage is achieved. The sensori-motor representations obtained by inversion were augmented
with VCV sequences from the original X-ray database, i.e. 78 vowels and 18 occlusives. The so-called Articulotron is supposed to have now sufficient sensori-motor representations of context-dependent exemplars of the sounds. These internal representations are sampled at the temporal landmarks delivered by the Perceptron. We selected two landmarks:

- Vocalic targets defined as points of maximum spectral stability
- Consonantal targets defined as points of maximal occlusion

4.1. Characterising targets

Targets are defined as compact regions of the sensori-motor space. We supposed that separate control channels for different classes of sounds are built: here two channels, one for the vowels and one for the voiced plosives. On these control channels, phonemic targets have been implemented as simple Gaussians: the force field is created by the derivative of the probability function (see section 5). A simple Gaussian has the advantage of generating a simple force field with no singularities and builds up intrinsically a compactia constraint. The sensori-motor space is divided into three sub-spaces:

- The articulatory space consisting of 8 articulators
- A geometric space consisting of 5 parameters: the area of the lips (Al), the area (Ac) and location (Xc) of the main constriction and two mid-sagittal distances: the minimum distances of the tongue tip (TT) and tongue dorsum (TD) to the palate. These two latter parameters are similar to those used in [13].
- An acoustic space consisting of the first three formants.

4.2. Sensori-motor sub-spaces

A Canonical Discriminant Analysis was performed and the vocalic and consonantal targets were projected on the first discriminant planes (see Fig. 2).

Vowels The examination of the structure of the projections and of the identification scores demonstrates that vowels are best defined in acoustic terms. Some additional arguments may be given in favour of an acoustic control of vocalic trajectories:

- The most successful procedure for predicting vocalic systems [9] uses a basic criterion of maximal acoustic dispersion of vocalic targets. Although a perceptual weighting of the solutions improves the prediction of the most frequent systems up to 9 vowels, articulatory or geometric data only shape and weights the dimensions of the maximal space.
- Recent perturbation experiments show that speakers tend to reach the same perceptual/acoustic goals with articulatory strategies that greatly differ from the unperturbed case [14].
- Vocalic trajectories tend to be linear in the acoustic space when it is re-analysed in terms of resonances [4].

Occlusives On the other hand, the voiced occlusives are best defined in terms of place of articulation. When the acoustic information is sampled at the vocalic onset as proposed by [15], the identification score is just above chance while the geometric score still rates 97%. Of course, the paradigm of relational invariance may hold but a context-independent target is no longer available.

Figure 3: A simple modulation of the acoustic force-field generating [n] from the neutral posture. From left to right, top: F2/F3 versus F1 and TT/TD versus Al. Note the quasi-linear3 trajectory in the F2/F2 plane. Bottom: Resulting formant trajectories (thick lines in a Bark scale) superposed with emergence functions (thin lines) and resulting articulatory gesture. Here tongue dorsum and jaw raise whereas tongue tip lowers and lips close. The tongue body is pulled back.

5. Voluntary motion by modulating force fields

Once sensori-motor representations of sound targets have been built, we have to verify that sound sequences can effectively be generated using a composite and superpositional control of attractor fields.

5.1. Vowels

First, we have to verify that vocalic sounds may be produced and chained adequately and that force fields generated in a structured acoustic space still pull articulatory gestures towards prototypical articulatory targets. The movement equation is: \( \delta A_{t} = \alpha \cdot p_{\text{mov}}(J_{t}, \delta A) \cdot A \), where \( \delta A \) and \( \delta A_{t} \) are respectively the resulting driving acoustic force and the back-propagated articulatory velocity. The driving force equals the sum of the gradients of the probability function for each vowel \( V \) weighted by its emergence \( k_{V}(t) \).

Each probability function is defined by its mean \( \text{mean}_{A_{t}} \) and covariance matrix \( \text{cov}_{V} \). Only the acoustic characteristics of the vocalic targets \( \delta A_{t} \) are considered as follows:

\[
\delta A(t) = \sum_{V} k_{V}(t) \cdot \left( \text{cov}_{V} \right)_{A_{t}} \cdot (\text{mean}_{V})_{A_{t}} - A(t) \]

where...
\[ \sum_{k} c_k(t) = 1. \] Fig. 3 shows the acoustic, geometric and articulatory trajectories produced by modulating the force field from the neutral attractor towards the /u/ vowel.

\[ \text{activations/formants} \]

\[ \text{articulators} \]

\[ \text{articulators} \]

Figure 4: Starting from the neutral posture the acoustic force-field generating [a] is perturbed by the [b] geometric attractor characterised by first principal axis at \( A_1 = 0 \).

5.2. Occlusives

We have shown above how articulation may be driven by a back-propagated modulation of an acoustic field. We suppose here that this carrier acoustic gesture is primarily modulated by vocalic targets whose emergence functions are characterised by slow and overlapping transition functions whose sum equal to one. We have shown that this carrier gesture may react to unexpected articulatory perturbations [6]. Occlusives may be seen as voluntary perturbations (see Fig. 4): the geometric trajectory deviates from the one produced by the acoustic driving field because of emergence of plosive-specific geometric attractors.

6. Conclusions

We described here a strategy for giving an articulatory model the "gift of speech" i.e. a learning paradigm that will enrich its internal representations from experience. These internal sensori-motor control are emergent because they are by-products of a first global audiovisual-to-articulatory inversion. Thanks an appropriate selective use of these representations the controller produces skilled actions and reacts to unexpected perturbations. Consonants may be seen as planned perturbations. We have to extend this paradigm to other consonants than those studied here. The next step is the learning and control of timing: how temporal relationship can be implemented both in terms of sequential and dynamic constraints and phasing between articulation and phonation can be handled.

7. references


Sound File References:

[qaba.wav]
[qabi.wav]
[qada.wav]
[qaga.wav]