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COMPUTATIONAL MODELLING OF SPEECH PRODUCTION

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INTRODUCTION

This paper outlines the basis of a computational model of speech production which focuses on contributing to an understanding of detail present in an acoustic speech signal but which has so far eluded satisfactory explanation. This is an extension of the SPRUCE speech production model reported earlier [Tatham, Morton and Lewis 1998, 2000]. Descriptive models which have no computational basis are difficult to test and evaluate, and so do not really help in establishing the theory they exemplify. In addition current models are not complete: it is usually not possible to trace a potential utterance through all its phonological and phonetic stages to arrive finally at an articulation or acoustic signal.

Central to any computational model is a set of clear formalisms for the main data structures involved. Two considerations are important:

- what are the elements needed within the data structure;
- what is the most appropriate formalism.

In this paper we give examples of a few of the main data structures we believe to be necessary, and explain the formalisms used.

But above all a computational model must be complete and coherent; if it is not the computation will fail. By reason of its completeness the model is inherently testable – it either runs or it does not: either way weaknesses and areas needing more development will point toward establishing the basis for formal hypotheses for empirical investigation.

The theory of speech production assumes that an exhaustive and generalised description of speech production needs to exist separately from dynamic instantiations of any particular utterances. We think of the generalised characterisation as a static representation which provides the basis of a plan for a particular utterance. We propose a reasoning [Tatham 1986c] Cognitive Phonetic Agent which selects the appropriate structures from the static representation in order to render the utterance dynamically. The term *dynamic phonetic rendering* is explained.

We illustrate the model by taking a single sentence and tracing it through several phonological and phonetic processes of planning and rendering to arrive at a symbolic representation of how the utterance will finally be articulated. Along the way we show how the various data structures are manipulated. The processes we have selected for illustration exemplify problem areas in the theory, and give us the opportunity to discuss the various formalisms used. In particular we have concentrated on the theory's overall prosodic framework and the way we have introduced a good first approximation to modelling expression in speech production.

SCOPE OF THE MODEL

The theory of speech production we are dealing with depends on the idea that speakers know in general about the processes used in formulating utterance plans (phonology), and about what is involved in rendering utterance plans (phonetics). This aspect of the model is developed on what we call its *static plane*. The word *plane* is used because it is useful to think of the model as having more than two dimensions, involving more than one plane. We label this plane *static* because it is a fixed and simultaneous characterisation of everything which from a linguistics point of view contributes to the planning and rendering of *all* utterances in the language.

Parallel to the model's static plane is a *dynamic plane*. It is here that the plan for any one utterance is developed by drawing on information held on the static plane. Because the static plane holds the information needed for formulating all utterances it must have the information necessary for developing any single utterance. Fig. 1 shows the relationship between the static and dynamic planes, together with, on the static plane, distinct sets of phonological and phonetic processes, and on the dynamic plane, an area on which a single utterance plan is developed (its unique phonology) and an area on which its plan is rendered (its unique phonetics). The model can trace the history of a single instantiation of a speech waveform rather than just enumerate the entire knowledge base supporting it.

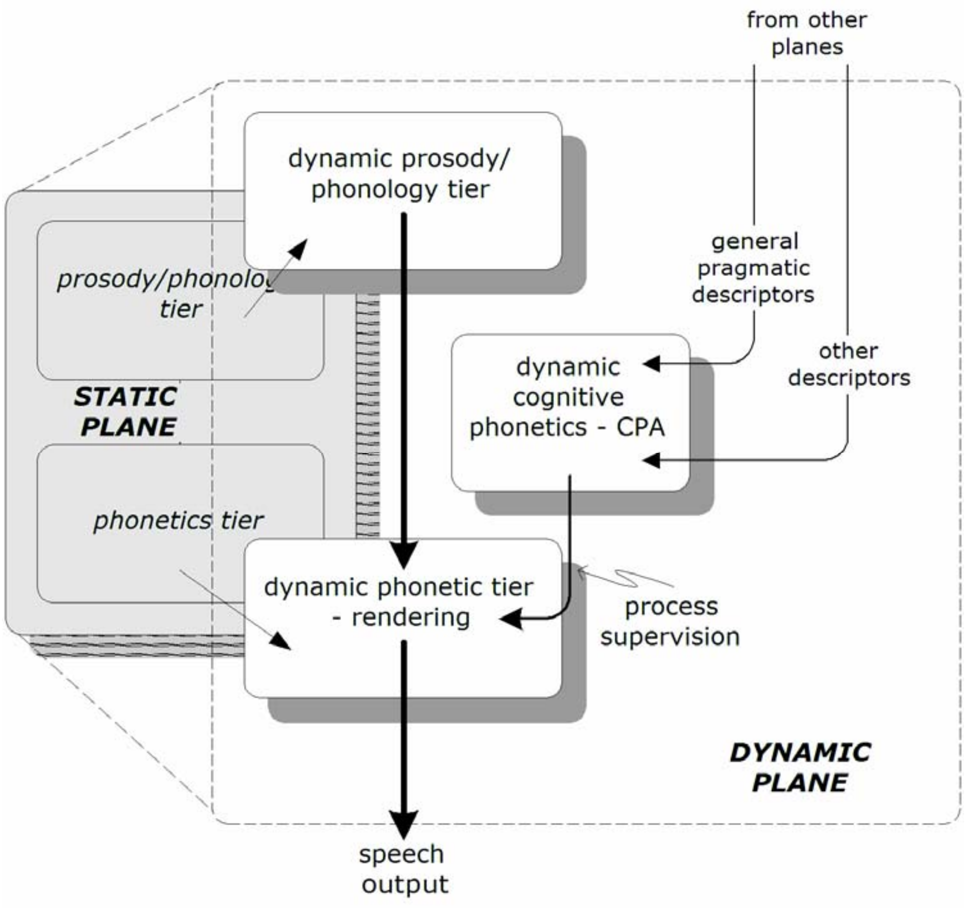


Fig. 1 The multi-dimensional model showing the static plane *behind* the dynamic plane. Each plane has a prosody/phonology tier and a phonetic rendering tier. Here the Cognitive Phonetic Agent is shown directly supervising phonetic rendering dependent on descriptors from other areas of the model.

But if the dynamic development of the plan for a unique utterance and its subsequent rendering depend on information held on the model's static plan, it becomes necessary to set up the means to select and bring appropriate 'objects' and processes from the static plane to the dynamic areas. We do not think of the procedures for drawing on static information as purely automatic. They are developed here as informed and intelligent procedures which need special mechanisms. We call these mechanisms *agents*, confining ourselves in this paper to some details of our Cognitive Phonetic Agent whose supervisory role has been described elsewhere [Tatham 1994].

One area of speech production theory in need of development concerns how to account for expression. Expression in speech could be characterised very abstractly in terms simply of generalisations and a speaker's potential for delivering expressive speech; but we feel that an understanding of what expression in speech is and how it forms part of almost every utterance speakers make requires a focus on the individual utterance and its subsequent rendering. We claim that utterances without expression can only exist in the abstract. A dynamically rendered utterance *must* have expression and the model must incorporate the means of explaining the utterance's expressive content. It falls to the Cognitive Phonetic Agent to supervise expressive content.

COGNITIVE PHONETICS AND SUPERVISION

We have argued before [Tatham 1986a] that there is a need to explain the manipulation of intrinsic physical processes in speech production. Such processes include coarticulation, and although they are intrinsic to the system and might at first glance be a-linguistic in origin they can sometimes get involved in the linguistically motivated encoding process in very subtle ways. For example, simple coarticulation effects are unplanned and are the result of juxtaposed articulations; but these effects can be often be overridden and seem to be under cognitive control. We have grouped processes where cognition influences intrinsic physical processes under the heading of Cognitive Phonetics [Morton 1986, Tatham 1986b, Code and Ball 1988, Cawley and Green 1991], and distinguished these processes from truly phonological cognitive processes performed uniquely on phonological objects. Thus Cognitive Phonetics and the cognitive processes of phonology are defined in terms of the domain of the objects on which they operate: phonological processes manipulate phonological objects, Cognitive Phonetic processes manipulate phonetic objects.

Following early work we later extended the principles of Cognitive Phonetic Theory to account for what we felt had to be a managerial role for the group of processes involved. We noted that the precision of controlled physical processes varies enormously – not just because of intrinsic factors but because of deliberate tightening or relaxing of the precision of articulation. This varying precision turned out to be principled.

Thus we introduced the idea of supervision in speech production [Tatham 1995]. Supervision involves a pre-determined level of *accuracy* and a deliberate attempt to maintain that level of accuracy. All the functions of a control system are invoked, in particular feedback and the response to on-going success in maintaining the required level of precision.

The current computational model invokes a Cognitive Phonetic Agent (the CPA) – a device dedicated to supervising the overall rendering process. The CPA takes its instructions from a number of different sources (Fig. 1), and manages the rendering process to produce the desired articulation or acoustic signal goal. The signal in turn reflects underlying generalisations about speech, but at the same time reflects this continuously varying precision and the accompanying expressive content.

SOME DATA STRUCTURE DETAILS

Central to any computational model is a clear representation of the various data structures involved. In this section we highlight some of the main data structures of the speech production model, and illustrate their organisation with some examples. A characterisation of data structures begins with their general case. In this model, the general case is represented on the static plane.

Much of the model is formalised in XML – a declarative language designed for characterising hierarchically structured data, and to make the characterisation suitable for subsequent procedural processing. A data structure is set out as an XML-schema which indicates in a formal way its most general case, including all constraints on its content. The rules governing XML-schema are complex, and a good way of approaching what XML can do is to focus on a very simple example which we are familiar with from a more traditional approach in phonology.

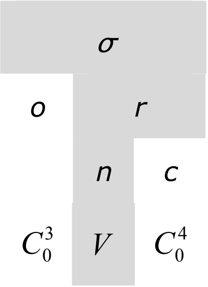
A simple declarative data structure: the syllable

The most useful hierarchical model of the syllable in traditional metrical phonology (Hayes 1995) looks like this:

σ → onset + rhyme
rhyme → nucleus + coda
onset → C_0^3
nucleus → V
coda → C_0^4

where σ is a syllable, C_0^3 means a number of consonants from zero to three, and C_0^4 a number of consonants from zero to four; V is the vowel.

or, in tabular or graphical form:



σ		
o	*r*	
	n	*c*
C_0^3	V	C_0^4

where σ is a syllable, *o* is the onset, *r* the rhyme, *n* the nucleus and *c* the coda, C_0^3 means a number of consonants from zero to three, and C_0^4 a number of consonants from zero to four; V is the vowel.

The shading in the table represents the part of the internal derivation which in traditional terms is not optional – that is, must produce a surface element. This is the direct path σ → *r* → *n* → V . The alternative is to regard everything as not optional, but indicating that the onset C_0^3 and the coda C_0^4 have the zero instantiation option which is not to be regarded as a null element. The approach taken will depend on whether some surface detail in the eventual phonetic rendering is dependent on the influence of an underlying element formerly considered optional.

For our development work in XML we use the integrated development environment created by Altova GmbH and Altova Inc [Altova 1998-2001]. Expressed as an XML-schema the syllable data structure looks like this:

```
<?xml version="1.0" encoding="UTF-8"?>
<xs:schema>
      <xs:element name="syllable">
         <xs:annotation>
            <xs:documentation>prosodic object</xs:documentation>
         </xs:annotation>
         <xs:complexType>
            <xs:sequence>
               <xs:element name="onset">
                  <xs:complexType>
                     <xs:sequence>
                        <xs:element name="consonant" type="xs:anySimpleType" minOccurs="0"
maxOccurs="3"/>
                     </xs:sequence>
                  </xs:complexType>
               </xs:element>
               <xs:element name="rhyme">
                  <xs:complexType>
                     <xs:sequence>
                        <xs:element name="nucleus">
                           <xs:complexType>
                              <xs:sequence>
                                 <xs:element name="vowel" type="xs:anySimpleType"/>
                              </xs:sequence>
                           </xs:complexType>
                        </xs:element>
                        <xs:element name="coda">
                           <xs:complexType>
                              <xs:sequence>
                                 <xs:element name="consonant" type="xs:anySimpleType"
minOccurs="0" maxOccurs="4"/>
                              </xs:sequence>
                           </xs:complexType>
                        </xs:element>
                     </xs:sequence>
                  </xs:complexType>
               </xs:element>
            </xs:sequence>
         </xs:complexType>
      </xs:element>
</xs:schema>
```

At first glance this structure looks complex, but in fact it is based on a simple markup system of hierarchically nested elements, complete with attributes. A schema is equivalent to a tree diagram in linguistics: it captures structural generalisations but does not, except by implication, detail a particular instantiation of an object. However, in our computational model it is necessary to provide specific utterance instantiations. These are formatted as an XML object which must be validated against the corresponding XML-schema. So, for example, the XML characterisation of a *particular* syllable must be tested against the XML-schema characterisation of syllables *in general* and shown to be valid. The XML code always points to its validating XML-schema (see line 2 in the following code where the schema *syllable.xsd* is referenced). The first line of the code has to name the XML version - in fact the only version currently available, as well as the basis of the character encoding.

An instantiation deriving from the general case is easier to follow than its corresponding XML-schema. The example below is the coding for the mono-syllabic word *streets* /striːts/. The first line declares the version of XML being used, and the second line indicates that the instance conforms to the general syllable XML-schema (called *syllable.xsd*) which we saw above.

```
<?xml version="1.0" encoding="UTF-16"?>
<syllable SchemaLocation=”./syllable.xsd">
   <onset>
      <consonant> str </consonant>
   </onset>
   <rhyme>
      <nucleus>
```

```
         <vowel> iː </vowel>
      </nucleus>
      <coda>
         <consonant> ts </consonant>
      </coda>
   </rhyme>
</syllable>
```

where <element> means ‘start of an element’, and </element> means ‘end of an element’ – these can be collapsed to <element/> (= there is an element which starts and ends here) if necessary.

In this XML model of the syllable /striːts/ we find the three-consonant sequence /str/ identified as the onset, the vowel /iː/ identified as the nucleus within the rhyme. The two-consonant sequence /ts/ is identified as the coda, also within the rhyme. The nucleus and coda stand in a logical AND relationship – that is the coda logically follows the nucleus and must exist (even if it includes zero consonants).

Although one purpose of the XML-schema is to capture the overall general structure of a syllable, it is also used to validate any proposed instantiation as a check on conformity. A validation parse of the model for /striːts/ shows it conforms to the XML-schema *syllable.xsd*. The parse is performed by traversing the tree structure of the XML declaration and checking that each node is a valid instantiation of the general case.

In the overall computational model of speech production this parse is important because it enables identification of the various nodes in an instantiation and establishes their relationship with each other – that is, it characterises their context. This in turn enables subsequent processing to operate properly on the correct object. As a very simple example, in our monosyllabic word *streets* we may need to render phonetically the onset /t/ quite differently from the coda /t/; this would reflect their position or context within the syllable. In turn the position of the syllable within the wider prosodic structure of the entire utterance would also enter into the detailed rendering of the various segments within the syllable. We shall see later that the dominant framework entering into the detail of phonetic rendering of the entire utterance is its prosodic structure.

It is useful to view an XML-schema graphically, and this is the format used from now on in this article. Fig. 2 is the tree diagram associated with *syllable.xsd*, while Fig. 3 shows the tree diagram associated with *rhythmic_unit.xsd* – the XML-schema for rhythmic units. In the prosodic hierarchy rhythmic units dominate syllables and impose constraints on their occurrence.

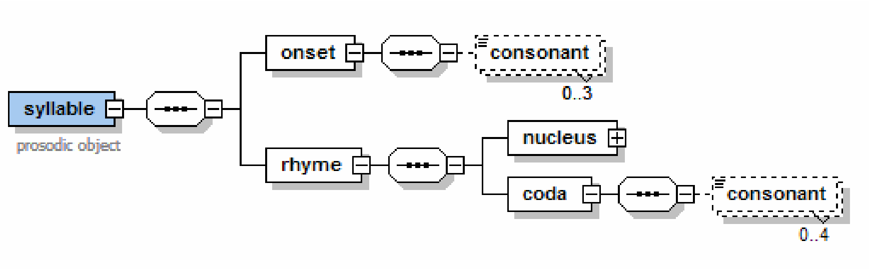


Fig. 2 Tree diagram of *syllable.xsd*. The dotted consonant elements indicate that they include a zero option as well as a sequence of up to 3 or 4. The nodes linking elements indicate *sequence* rather than *choice* – that is, the descendent elements are in a logical AND relationship rather than an OR relationship. Thus if we have an onset descendent from element *syllable*, we must also have a rhyme element. Below each consonant element is an annotation indicating the minimum and maximum number of occurrences of the consonant object.

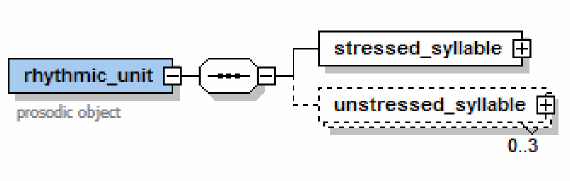


Fig. 3 Collapsed tree diagram of *rhythmic_unit.xsd*. The immediate descendents of the rhythmic unit element are, in sequence, a stressed syllable followed by zero or up to three unstressed syllables (the occurrence of 4 or more unstressed syllables is rare). The unstressed syllable is dotted to indicate that it may not be present.

Fig. 4 shows the expanded tree for *rhythmic_unit.xsd* – right down to the terminal elements: vowels and consonants. Each syllable is structured according to the syllable schema *syllable.xsd* and descendent to the rhythmic unit.

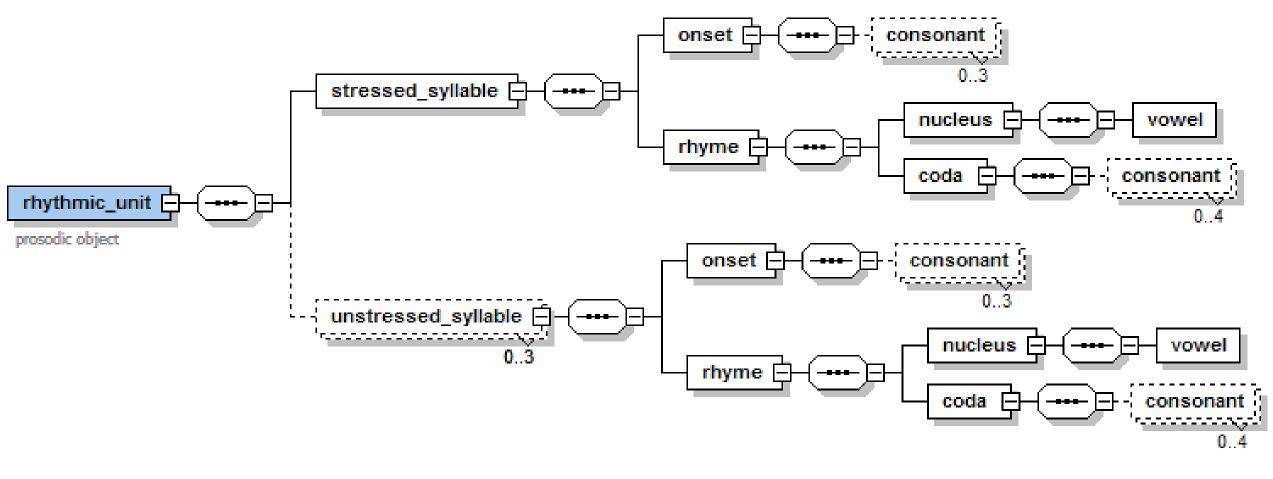


Fig. 4 Expanded tree diagram of *rhythmic_unit.xsd*. The sequence 'stressed syllable followed by zero to 3 unstressed syllables' is expanded to include the data structure associated with syllables. Elements which can have a zero presence are enclosed in a dotted box.

The prosodic framework for utterances

Utterance plans in our computational model are derived within an overall prosodic framework which itself is declared in XML. Syllables are the basic units of prosody, and as we saw from Figs. 2 and 3 they relate sequentially *via* a dominant rhythmic unit. In turn rhythmic units (of which there must be at least one) sequence within an accent group, and accent groups sequence within intonational phrases.

The overall framework is a prosodic one since the phonetic rendering of utterances depends on their prosodic structure, including the detail of the structure of the syllable – the basic unit of the prosody. The idea is not novel (see Firth 1948 on the prosodic structure, and Kahn 1976 and Gussenhoven 1986 on the structure of syllables, in particular the phenomenon of ambisyllabicity and detailed phonetic rendering), and it forms the basis of the conceptual design of the SPRUCE computational model [Lewis and Tatham 1991, Morton and Tatham 1995].

In a traditional notation the most general case of the prosodic framework is:

$$IP \rightarrow AG\ (AG\ ...) \rightarrow (...\rho)\ \rho\ (\rho\ ...) \rightarrow \sigma\ (\sigma\ ...) \rightarrow (o)\ r \rightarrow n\ (c)$$

where *IP* = intonational phrase, *AG* = accent group, *ρ* = rhythmic unit, *σ* = syllable. Syllables take the traditional *onset* + *rhyme (→ nucleus* + *coda)* form. Optional elements are bracketed.

To avoid confusion over rhythm units we do not use the term *foot* here. Elsewhere [Tatham and Morton 2001] we distinguish between the traditional term *foot* (which indicates a general abstract unit of rhythm to which listeners and speakers are sensitive) and the term *rhythmic unit* to indicate a quantifiable instantiation of *foot*. In this paper we shall use only *rhythmic unit*.

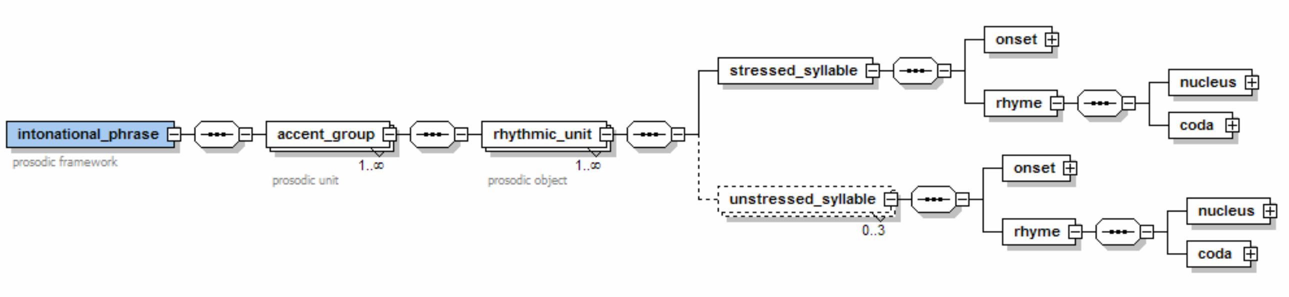


Fig. 5 The prosodic framework modelled as an XML-schema. The figure shows the graphical representation of the schema down to the general syllable structure elements of the tree.

Fig. 5 is a graphical representation of the XML-schema *prosodic_framework.xsd* down to the syllable structure elements. The initial dominant element is the intonational phrase below which there must be at least one accent group (with the upper limit open). In turn the accent group dominates at least one rhythmic unit. As before any XML instantiation of this general case schema can be validated against the schema and appropriately parsed for further processing.

Utterances are planned *within* this prosodic framework; thus prosody is not something which is added to utterances at some lower level. The reason for this is that detail of actual utterances is dominated by prosodic structure (e.g. the effects of stress and rhythm on vowel quality, the effects of ambisyllabicity on plosive release [Ogden *et al* 2000]), and interactions between elements within the structure. We give some examples later of prosodically dominated processes operating on segmental elements (see the section *Phonetic rendering on the dynamic plane's phonetic tier*). Meanwhile, let us continue with some more examples of data structures within the computational speech production model.

Below syllable level – segment gesture data structures

The word *segment* on its own is used in the model for elements at the phonological level; at the phonetic level we speak of *segment gestures*. In recent times the term *gesture* has been associated with the Articulatory Phonology speech production model [Browman and Goldstein 1986] but the term had been used extensively by previous writers (*cf*. its use in Paget 1930 and Abercrombie 1967).

The model adopts the established classification of two types of segment gesture: consonant and vowel (Ladefoged 2001). We express the data structures for these types in term of the object-oriented paradigm. This particular paradigm has been chosen because the data structure associated with segment gestures is essentially flat – that is, it does not have the deep hierarchical composition of the earlier prosodic framework examples.

Segment gestures are objects with a general structure identifying a number of parameters and indicating their computational type. The parameters specify phonetic articulatory goals and use a terminology which is for the most part familiar in articulatory phonetics. The computational types are markers for the appropriate attributes of each goal. Notice that many parameters are doubled up; thus, we have 'place1_oral' and 'place2_oral'. This is to allow for specifying the structure of *bi-phasal* and *bi-polar* gestures. A bi-phasal gesture is one which has a sequence of two constriction goals (e.g. [t] with a stop phase followed by a release phase), and a bi-polar gesture is one with two place goals (e.g. [ai] – a diphthong with different start and end points in the vowel space). The robustness parameter is an indicator of how resistant the gesture is to externally derived factors such as coarticulation. It is arguable that this choice of parameters is an oversimplification of the phonetic facts – but we stress we are dealing with a first approximation model focusing on data structure: detailed representation comes later.

The general case for a consonant gesture of 14 parameters is:

```
consonant_gesture = object
   type:               string;
   robustness:         real;
   place1_non-oral:    string;
   place2_non-oral:    string;
   place1_oral:        real;
   place2_oral:        real;
   place1_extraoral:   string;
   place2_extraoral:   string;
   constriction1:      real;
   constriction2:      real;
   round:              real;
   nasal:              real;
   glottis1:           real;
   glottis2:           real;
end;
```

And a vowel gesture is an object with the following general structure of 12 parameters:

```
vowel_gesture = object
   type:               string;
   robustness:         real;
   place1_oral:        real;
   place2_oral:        real;
   constriction1:      real;
   constriction2:      real;
   round:              real;
   nasal:              real;
   glottis1:           real;
   glottis2:           real;

end;
```

where ‘real’ is a real number, either 0 to +1, or -1 through 0 to +1. String is a text string like *lips*, etc. These are data types in the traditional sense.

Vowel gestures can only have an oral place (that is, their traditional front/back place must be in the vowel space). But consonant gestures can also have a non-oral or ‘extra-oral’ place: lips, lips/teeth, teeth, velum, pharynx, glottis. We find it useful to identify those *consonant* gestures which have a *vowel*-space affinity – we feel that vectors like: [t] ⇢ [s] ⇢ [ʃ] ⇢ [i] ⇢ [ɛ] ⇢ [æ] are important conceptually although it appears that we have switched from consonant to vowel midway. In traditional terms the start place for this vector is the alveolar ridge, a value of 0.8 (see below for more detail on the meanings of these values). It is helpful to think of the vector as a line on a traditional vowel chart moving from the alveolar ridge down to the spot used to mark [æ]. This line passes through all the segments in the sequence, which could be regarded as zones on the vector, or categories through which the vector moves.

The segment gestures of English on this vector all share place 0.8 and have, respectively, constrictions with values: 1 ⇢ 0.8 ⇢ 0.7 ⇢ 0.5 ⇢ 0.3 ⇢ 0.1. The constriction 1 is important because it actually signifies ‘*beyond* the palate’; the use of the concept *beyond* guarantees the required contact pressure for the plosive, whereas 0.9 which is for taps signifies ‘*at* the palate’ with insufficient contact pressure to hold back the airstream other than momentarily – a condition never tested because the contact time is always too small (except for rolls where the contact pressure is low and the time is long). A bilabial roll, for example, would be ‘type: bi-polar (place focus), place1: lips, place2: lips, constriction1: 0.9, constriction2: 0.9’, whereas a bilabial stop would be ‘type: bi-phasal (constriction focus), place1: lips, place2: lips, constriction1: 1, constriction2: 0’, and a bilabial tap would be ‘type: bi-phasal (constriction focus), place1: lips, place2: lips, constriction1: 0.9, constriction2: 0’.

These general data structures are declared on the phonetic tier of the static plane. This is where they are also instantiated to give us the general set of segments available for the language. Here is an example of two instantiated consonant objects, [t] and [r]:

```
var
   [t] : consonant_gesture;

[t].type            = bi-phasal
[t].robustness      = 0.5
[t].place1_oral     = 0.8
[t].place2_oral     = 0.8
[t].constriction1   = 1
[t].constriciton2   = 0
[t].round           = 0
[t].nasal           = 0
[t].glottis1        = 0
[t].glottis2        = 0
```

where [t] is an object of type consonant, thereby inheriting the set of variables defined as being those which characterise a consonant object: viz. {type, robustness, place1_oral, place2_oral, constriction1, constriction2, round, nasal, glottis1, glottis2}, and these variables are instantiated for [t] as listed. The variables for consonant objects which do not appear here are either not applicable or random.

```
var
   [r] : consonant_gesture;

[r].type            = bi-phasal
[r].robustness      = 0.9
[r].place1_oral     = 0.5
[r].place2_oral     = 0.6
[r].constriction1   = 0.2
[r].constriction2   = 0.3
[r].round           = 0.1
[r].nasal           = 0
[r].glottis1        = 0.8
[r].glottis2        = 0.8
```

where [r] is an object of type consonant, inheriting the characteristics of a consonant object, and these are instantiated as shown for [r]. As before irrelevant parameters are not listed. [r] is of type bi-phasal because there is constriction change during the segment.

And similarly, two vowels: [ɒ] and [aɪ]

```
var
   [ɒ] : vowel_gesture;
[ɒ].type            = uni-polar
[ɒ].robustness      = 0.9
[ɒ].place1_oral     = 0.1
[ɒ].constriction1   = 0.2
[ɒ].round           = 0.2
[ɒ].nasal           = 0
[ɒ].glottis1        = 0.9
```

where [ɒ] is an object of type consonant, inheriting vowel prototype parameters, properly instantiated here for [ɒ]. Notice that short monophthongs (as in this example) are of type uni-polar, but long monothongs are of type bi-polar allowing for characterisation of their almost universal tendency to diphthongise slightly.

```
var
   [aɪ] : vowel_gesture;
[aɪ].type           = bi-polar
```

```
[aɪ].robustness      = 0.9
[aɪ].place1_oral     = 0.5
[aɪ].place2_oral     = 0.7
[aɪ].constriction1   = 0.1
[aɪ].constriction2   = 0.4
[aɪ].round           = 0.1
[aɪ].nasal           = 0
[aɪ].glottis1        = 0.9
[aɪ].glottis2        = 0.9
```

where [aɪ] is an instantiation of the vowel prototype with parameters appropriately assigned. Diphthongs are of type bi-polar to enable place shift to be described. 'Vowelness', that is, what constitutes a vowel, is inherited from the general case characterisation, with appropriate values assigned for this particular vowel.

Objects also have methods – procedures which the object embodies. That is, these static descriptions just discussed are enhanced with functional information that the object knows about its own behaviour. We do not discuss this property of phonetic or phonological objects here except to say that the model allows for segment gesture behaviour to originate from within the gesture as well as be determined from outside. All object oriented systems have this property – the major characteristic distinguishing them from simple procedural systems. We first applied the object oriented paradigm to a computational characterisation of Action Theory's coordinative structures [Fowler 1980] because the coordinative structure model fitted the paradigm remarkably well.

Additionally the object oriented paradigm permits *inheritance* in a similar way to the declarative XML paradigm used here to characterise the prosodic framework for speech production. Properties associated with a higher node or parent declaration (the general case) are inherited by lower nodes or child declarations. For example, an instantiation of *consonant_gesture*, say [t], is said to inherit its parent properties, that is, all those assigned to the dominant general case, *consonant_gesture*.

THE COGNITIVE PHONETIC AGENT AND PHONETIC RENDERING

The Cognitive Phonetic Agent (CPA) works to supervise phonetic rendering, making sure that the output of the reasoned rendering processes is optimal. To do this the CPA needs various pieces of information to decide what constitutes an optimal rendering and how to achieve it on any one occasion.

An optimal rendering is one which achieves the goal of promoting a good percept in the listener's mind. The perceptual system is such that there is not just a single rendering which is optimal. There is a range of renderings all of which can be accommodated by the listener, by a process of 'repair', in arriving at the right percept. The range describes a bell shaped curve with the effectiveness of repair lessening toward its edges. The CPA is aware of this because it understands how the repair process works and what its limitations are – *it incorporates a model of the repair process*.

The essential property of rendering we need to focus on is that it is an active dynamic process which brings additional information and data to developing an articulation from the basic utterance plan. The rendering process has more than the phonological plan as its input. In addition there is a supervisory input bringing considerations of expressive content to the rendering process.

An analogy can be made here with computer graphics in which a rendering process takes a simple wire frame model of a 3D object and paints it with colour and texture, and provides an illuminating light source together with appropriate shadows. The rendered object derives from the basic wire frame by the addition of graphical 'expression' involving interpretation of the plan in the light of such expressive demands. We use the tern 'render' in a similar fashion: a simple wire frame utterance plan is rendered with the colour, texture, light and shade of expression to derive an articulation from which the original plan can be perceived but which also triggers in the listener perceptual correlates of the added expressive content.

AN EXAMPLE DERIVATION

In this example derivation we trace a short utterance through events on the dynamic plane of the speech production model. The *dynamic* plane is where CPA-driven algorithmic processes can occur, and this contrasts with the *static* plane which is reserved for groupings of simple descriptive processes akin to expected descriptions in the usual phonological and phonetic components of a grammar.

The model begins with an entry point to the speech production algorithm. Here the unique future utterance enters the system in the form of a *requirement utterance* – an object to be spoken. There are four main procedures on the dynamic plane, shared between the prosodic/phonological tier (concerned with formulating the utterance plan) and the phonetic tier (concerned with rendering the plan):

```
begin
{
        input (requirement_utterance);
        formulate_plan (requirement_utterance);
        render_plan (requirement_utterance);
        output (requirement_utterance);
}
```

The four main actions are to be performed on the requirement utterance specify that

a. it must be input into the speech production algorithm [phonological tier],
b. a plan for speaking it has to be formulated [phonological tier],
c. the plan has to be rendered [phonetic tier], and
d. the result has to be output [phonetic tier].

The requirement utterance which is input to the speech production dynamic plane (phonological tier) originates higher up in the system – it is equivalent to a string written down and which has to be spoken out aloud; in itself it has no sound shape other than a very minimal representation of some underlying phonological properties, just sufficient to enable the subsequent planning and rendering procedures which are part of the speech production process we are modelling to be performed.

So what does the requirement utterance look like? We declare the structure of an utterance again using XML since what we need is a hierarchically structured declaration to reflect the composition of the data structure. A specific utterance representation takes the form of an XML structure, but the general representation of all utterances takes the form of an XML-schema. Thus there would be a file called *utterance.xsd* specifying what any utterance must look like, and several files of which one would be a particular utterance called *utterance.xml* where *utterance* is the name of the actual utterance.

Here is a sample requirement utterance:

<sentence> bʌt wɒt s ðə fʊl prais </sentence>   *[But what’s the full price?]*

The highest level in the hierarchical description of this utterance declares the sentence domain. Other syntactic marking is present as necessary for subsequent phonological marking or analysis; though this is omitted in the example for the sake of clarity and because it is not central to the discussion here. The requirement utterance is immediately assigned the abstract prosodic framework (see above *The prosodic framework for utterances*) which is to form the basis or *wrapper* for all subsequent phonological and phonetic processing down to the level of motor control. An overview of phonological encoding and what the process might mean (movement from morphemic to phonological representation) is discussed by Keating [2000].

Assignment of the abstract prosodic framework

Here is the highest level declaration of our example sentence *But what's the full price?* after the assignment of the abstract prosodic framework. The framework for the utterance is dominated by `<IP/>`, and this forms the widest domain and container for the remaining prosodic units. This utterance consists of three sequenced (AND-ed) accent groups the first of which has one foot with two syllables (one stressed, one unstressed), the second a foot with two syllables (one stressed, one unstressed), and the third two feet each with a single stressed syllable. The notation is explained below the declaration.

```
<utterance>
  <IP>
     <AG>
        <foot>
           <syllable stressed="1">$</syllable>
           <syllable stressed="0"> bʌt </syllable>
        </foot>
     </AG>
     <AG>
        <foot>
           <syllable stressed="1"> wɒt s </syllable>
           <syllable stressed="0"> ðə </syllable>
        </foot>
     </AG>
     <AG>
        <foot>
           <syllable stressed="2"> fʊl </syllable>
        </foot>
        <foot>
           <syllable stressed="1"> prais </syllable>
        </foot>
     </AG>
  </IP>
</utterance>
```

where

- `<IP/>` is an intonational phrase: the domain of an intonation contour
  `<AG/>` is an accent group: an intonation unit
  `<foot/>` is a foot: an abstract unit of rhythm
  `<syllable>` is a syllable - the lowest coherent unit (node) of prosody, and in this system, the lowest coherent unit of prosodic phonology – that is, phonology within a prosodic framework
  `<syllable stressed="1">` is a stressed syllable, `<stressed="1">` is an attribute of `<syllable>`
  `<syllable stressed="0">` is an unstressed syllable
  `<syllable stressed="2">` is an nuclear stressed syllable
  $ is an empty stressed syllable to cater for rhythmic units at the start of an utterance with an apparently missing stressed syllable [Tatham and Morton 2001 and 2002], where hanging syllables in rhythmic structure are explained and discussed. The condition is that each foot must start with a stressed syllable; if it does not it is necessary to insert an empty stressed syllable).

IP (the intonational phrase) is the widest intonational domain treated here, and may often correspond to the syntactic domain *sentence*. Within the IP domain are accent group (AG) sub-domains – the domains of pitch accents. Notice though that there are no fully predictable IP or AG instantiation types (particular intonation contours) from the basic syntactic structure of utterances, except on a statistical basis. Rather, prediction comes from the yet larger framework of *expression,* and takes in communicative aspects of language extending in principle beyond the utterance. However, for the moment, let us just indicate this as

```
<EXPRESSION><utterance><IP><AG/+></IP></utterance></EXPRESSION>
```

where <EXPRESSION/> might be instantiated for example as *<tactful/>* or *<forthright/>* or some similar expression declaration*.* It seems reasonable to us to assume that expression would have the major influence (*via* the CPA) on the intonation contour type to be associated with how this particular utterance is to be spoken. Because expression seems to pervade all nodal processes of the utterance it is right that it should be located on a higher wrapper node. Of course expression as a 'way of talking' often changes during a communicative exchange, and our data structure must and does take care of this – enabling the node's varying content to influence intonation contour type and moment of change appearing lower in the structure[1].

[FOOTNOTE: [1]There is no space in this paper to argue the case for having the node <EXPRESSION/> dominating the utterance; let us just say that for the moment this arrangement seems to us to account for the data more satisfactorily than other arrangements. A single expression type usually spreads, for example, over one or more utterances rather than simply over part of an utterance.]

As discussed earlier <syllable/> is itself hierarchically organised into units of <onset/> and <rhyme/>, with <rhyme/> organised as <nucleus/> and <coda/>. Note that there is scope for the <coda/> content of one syllable spanning the <onset/> content of a following syllable – the phenomenon usually called *ambisyllabicity*. When the phenomenon does occur it is important in determining some of the detail in subsequent rendering processes, for example whether a voiceless plosive is followed by aspiration or not. However, Huckvale [1999] has noted a problem with representing ambisyllabicity in XML because the strict component hierarchy constraint in XML syntax forces element duplication by preventing membership of two branches of the tree by a single leaf – the very meaning of ambisyllabicity. We do not feel this to be a particularly serious constraint because element duplication is sometimes felt and reported by native speakers. It is true, though, that the phenomenon, called by us *element spanning*, is badly catered for in XML – see the next section *Ambisyllabicity*.

Ambisyllabicity

Ambisyllabicity occurs when the coda of a syllable and the onset of the following syllable overlap in the sense that there is no real certainty as to which syllable a particular element belongs. Take a polysyllabic word like *maker*. There is evidence of native speaker hesitation here when asked about syllable boundaries. Speakers can say that the word consists of two syllables, but some will hesitate when asked where the boundary is: some will report a structure like /mei.kə/ and others will say /meik.ə/. A linguist might say that /mei.kə/ is essentially a phonologically motivated structural description, while /meik.ə/ is a morphologically motivated description. Ambisyllabicity as a notion in phonology captures this ambivalence of the /k/ by assigning it to *both* the coda of the first syllable and to the onset of the second. Ambisyllabicity is the default solution for this kind of data, and holds so long as constraints on syllable structure are not violated – for example *makeshift* can only be /meik.ʃɪft/ - the sequence /…kʃ…/ is not permitted in either a coda or an onset.

In our model we assign an attribute *span* to the element *coda* where span is either true or untrue (0 or 1 respectively). If span is true then the consonant or consonant cluster in the coda can also be the onset of the next syllable in an ambisyllabic arrangement. Researchers are unclear at to the *direction* of ambisyllabicity. By this we mean that we have chosen to say that a coda consonant, consonant cluster or partial consonant cluster can span to a following onset (a left to right direction), but is it the case that we might equally have spoken of an onset consonant spanning to the previous coda (a right to left direction)?

Furthermore we feel that the right place to assign span is on the *coda* itself rather than on the lower consonant – our feeling is that it is the coda which overlaps rather than the lower consonant node. We keep this idea even when only part of a consonant cluster may be ambisyllabic, as in *selfish*, for example. We shall see later that ambisyllabicity has consequences for the rendering process where syllabic boundaries might be aligned 'to best predict allophonic variation' [Gimson, revised Cruttenden, 2001, p.52]. Gimson also uses phonological allophonic rules to assign syllable boundaries. So, for example, a word like *metal* would be /mɛt.əl/ or /mɛt.təl/, rather than /mɛ.təl/ to satisfy the observations that the word is pronounced in some accents as /mɛʔ.əl/ (/mɛ.ʔəl/ is not possible), that monosyllabic words cannot end in /ɛ/, and that this is a vowel which is shortened before a voiceless consonant in the same syllable.

We characterise this particular word as having its first syllable ending in a spanning coda, that is, as ending in an ambisyllabic coda. Thus we modify the basic syllable model to assign to the element <coda/> an attribute *span* which can take a Boolean value of 0 or 1: <coda span=(0 | 1) /> (meaning either 'this is a coda with no ambisyllabic element', or 'this is a coda with an ambisyllabic element').

Phonological rules used on the dynamic plane

Once the utterance requirement has been given a prosodic envelope it is possible to proceed through the phonological rules. Tiers on the dynamic plane are like blackboards under the control of intelligent devices we see as reasoning agents. We have already mentioned the CPA – the Cognitive Phonetics Agent. The prosodic/phonological reasoning agent equivalent to the CPA has two main functions:

- to scan the *static* prosodic/phonological tier to locate rules which fit the prosodic and phonological context descriptors of the utterance; then to import such rules and apply them – this whole process to be performed iteratively until no context descriptors remain;
- to invoke its supervisory capacity to manage the whole procedure, in order to use the prosodic/phonological processes appropriately, depending on pragmatic [Morton 1992] and other inputs, provided these constrain phonological processes.

So, the reasoning supervisor agent selects appropriate processes to apply to the utterance requirement. The procedure is not straightforward because there are additional inputs specifying conditions like attitude and emotion. For this reason it is unlikely that two utterance plans for a single utterance requirement would be the same. The reason for this is that at this point the supervisor agent exercises the role of systematically managing variations which are collectively perceived as 'expression'. We work on the assumption that no speech is without expression, and that expression is a continuous variable.

A straightforward planning process would result in an expressionless plan – and, if it is the case that plans are never expressionless a means must be established for interacting with the planning process to derive plans with expressive content. In our model the supervisor is responsible for varying the plan to include expression. The supervisor knows what expression is needed by carefully weighing up competing inputs sourced in pragmatics [Morton 1992, Morton and Tatham 1995], stylistic and other such tiers and planes. For the moment we are only discussing prosodic/phonological effects – but clearly phonetic rendering also includes variability conveying expressive content (see Fig. 1).

As an example consider that the utterance requirement *But what's the full price?* is to be spoken with authority. Authoritative style might, among other things, call for a positive release for the /t/ in *what's*. The speaker we have in mind might normally have an unreleased /t/ in this word, dissolving through affrication into the following /s/. We could argue whether the surface unreleased [t̚] is actually a coarticulated version of the released [t] in this instance (in which case a released [t] would be a cognitive phonetically constrained phenomenon), but we feel that here there is clear choice between released and unreleased /t/ at the phonological level. This is even more obviously the case when the /t/ occurs in true final position: speakers of several accents of English have a clear phonological choice between /wɒt/ and /wɒt̚/, though one form will dominate in some accents for some speakers and the other in other accents. One particular accent at least, Cockney English, will usually substitute /ʔ/ in both final and pre-/s/ positions [Wells 1982], lending weight to the argument that the alternation is phonologically determined since [ʔ] is not a coarticulated allophone of [t]. However this does not mean to say that some measure of coarticulation is not overlaid on phonological choices: for us coarticulation is all-pervasive – it's a question of teasing out the choice element from the final result and representing extrinsic events of choice consistently on the phonological tier, and intrinsic events on the phonetic tier [Ladefoged 1971, Tatham 1971] . Thus, in traditional notation:

$$T \Rightarrow \begin{bmatrix} t \\ +\, positive\_release \end{bmatrix} / \begin{bmatrix} coda \\ -/\,s\,/ \end{bmatrix}$$

That is, voiceless alveolar stops have positive release when in the syllable coda and preceding an /s/ which is also in the coda.

We feel, though, that phonetically there is no corresponding positive release for the final [t] in the word [bət̚], so we need to obtain from the static plane and import to the dynamic plane's prosodic/phonological tier a rule like

$$T \Rightarrow \begin{bmatrix} t \\ -\, release \end{bmatrix} / \begin{bmatrix} coda \\ -\# \end{bmatrix}$$

That is, voiceless alveolar stops are unreleased when at the end of a word.

So, part of sounding authoritative might involve a *careful* style. Suppose the speaker's normal accent is a casual Estuary English, then ordinarily the following rule might apply to the /l/ at the end of the word /fʊl/:

$$L \Rightarrow \begin{bmatrix} l \\ +\, vocalised \end{bmatrix} / V - \begin{Bmatrix} \# \\ C\# \end{Bmatrix}$$

where uppercase *L* is used for the underlying phonological segment /L/, *V* stands for any underlying vowel and *C* for any consonant; while *#* stands for word boundary.

That is, an underlying /L/ is planned as vocalised 'l', or /ʊ/, in syllable codas either immediately before the boundary or before some other consonant. Examples are *wall*, *melt*. However a careful style would call for a planning rule:

$$L \Rightarrow \begin{bmatrix} l \\ +\, velarised \end{bmatrix} / V - \begin{Bmatrix} \# \\ C\# \end{Bmatrix}$$

That is, a velarised ('dark') 'l' or /ɫ/ (sometimes written /l_w/) is to be used in the plan at the end of a word or before final consonants, rather than the vocalised alternative.

For the moment it does not matter whether we regard this as the selection of an alternative rule or as some kind of tightening of an existing rule, the point is that there has been an informed and supervised act of *choice* operating. The choice is dependent on considerations peripheral to or outside the usual prosodic/phonological planning processes. Here we are adding a dynamic, intelligent and choice-oriented planning agent to the usual more automatic set of procedures.

But our example authoritative style also involves speaking with more precision [Tatham and Morton 1980] – a matter for phonetic rendering. So far we have a phonological plan looking like this (detail of syllable composition has been omitted here):

```
<utterance E="authoritative">
   <IP>
      <AG>
         <foot>
            <syllable stressed="1"> $ </syllable>
            <syllable stressed="0"> bət̚ </syllable>
         </foot>
      </AG>
      <AG>
         <foot>
            <syllable stressed="1"> wɒt s </syllable>
            <syllable stressed="0"> ðə </syllable>
         </foot>
      </AG>
      <AG>
         <foot>
            <syllable stressed="2"> fʊɫ </syllable>
         </foot>
         <foot>
            <syllable stressed="1"> prais </syllable>
         </foot>
      </AG>
   </IP>
</utterance>
```

To summarise: The root *utterance* has now been given an attribute set *E* of which one member is authoritative. The attribute system allows for the names of other expressions to be included, for example: `<utterance E="happy">`. The utterance plan for *But what's the full price?* spoken carefully now has three accent groups within a single intonational phrase. The first two accent groups each contain one rhythmic unit and the third contains two rhythmic units. The syllables are: /.bət̚./ (with reduced vowel and unreleased /t/), /.wɒts./ (with a positively released /t/, /.ðə./ (with reduced vowel), /.fʊɫ./ (with velarised /l/), and /.prais./. Tonic or sentence stress falls on /.fʊɫ./ – '.' means 'syllable boundary'. Some choices of surface variant have been determined by the pragmatic consideration that the utterance is to be spoken authoritatively.

Phonetic rendering on the dynamic plane's phonetic tier

Our example sentence *But what's the full price?* began with a very abstract phonological representation which in more traditional terms would have been called phonemic: /$ bʌt wɒt s ðə fʊl praɪs/. The final phonological representation, still within the prosodic framework, is the utterance plan expressed here in what, in the same terminology, would have been called extrinsic allophones: /$ bət̚ | wɒt̚s ðə | ˈfʊɫ | praɪs/ (vertical lines mark rhythmic unit boundaries). A final rendering, still using traditional notation to express intrinsic allophones, includes all coarticulatory effects – that is, phonetically contextually determined variation: [$ ˁbə̊t̚ | wɒ̢t̠̚s ðə | ˈf̢ʊɫ̢ | pˁrais]. This section discusses how some of these allophones are derived during the rendering process.

Firstly, some notes on the principal coarticulation effects:

1. The [t] in the coda of [bət̚] is not ambisyllabic because in this accent (Estuary English; and also most North American English accents) it has release failure: we observe that only a fully released [t] (as in Standard British English) is ambisyllabic. Hence the onset of [wɒt̚s] is not [tw] and thus the single onset

segment [w] does not have appreciable vocal cord vibration failure (compare the start of onset of [pʽrais] which does have vocal cord vibration failure (VOT). Similarly the onset of [ðə] has no ambisyllabic consonant – so no appreciable vibration failure at the start of [ð].

2. The [ɒ] of [wɒ̹t̠̚s] has some perseverative lip-rounding from the preceding [w], and the [f] of [fʊɫ] has some anticipatory lip-rounding from the following [ʊ].

3. The [t̚] of [wɒ̹t̠̚s] is somewhat retracted following the back vowel [ɒ].

In general the coarticulatory effects present in the phonetic rendering of this utterance can be divided into those which have an aerodynamic basis and those which have a mechanical basis:

1. aerodynamically induced coarticulation
   - vocal cord vibration failure:
     [ʽb] – utterance onset [b]
   - partial vocal cord vibration failure:
     [ə̊] – unstressed inter-voiceless stop [ə]
   - partial vocal cord vibration failure:
     [ʽr] following syllable initial [p] (VOT)

2. mechanically induced coarticulation
   - lip rounding:
     [ɒ̹] after syllable initial [w]
   - retraction:
     [t̠̚] following [ɒ]

Below is the utterance plan (extrinsic allophonic representation) data structure expressed as a feature matrix after it has had some physical detail added at the start of the phonetics tier. The phonetic information has come from the phonetics tier on the static plane. The following have been added as the processes move from segment to segment gesture

1. segment gesture type (uni- or bi-phasal (focuses on constriction), uni- or bi-polar (focuses on place)
2. robustness (an index of how vulnerable the segment gesture is to constraints such as coarticulation)
3. place details
4. constriction details
5. roundness and nasality details
6. glottal details

   [Note that bi-phasal and bi-polar gestures require two values for place, constriction and glottal parameters.]

	b	ə	t̚	w	ɒ	t̚	s	ð	ə	ˈf̹	ʊ	ɫ	p	r	aɪ	s

type	bi-phasal	uni-polar	uni-polar	bi-phasal	uni-polar	uni-phasal	uni-polar	uni-polar	uni-polar	uni-polar	uni-polar	bi-polar	bi-phasal	bi-polar	bi-polar	uni-polar
rob.	0.3	0.7	0.5	0.9	0.9	0.5	0.7	0.9	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.7
place1	lips	0.5	0.8*	lips	0.1	0.8*	0.8*	teeth	0.5	lips/teeth	0.2	0.2	lips	0.5	0.5	0.8*
place2	lips											0.2	lips	0.6	0.7	
constr1	1	0.3	1	0.5	0.2*	1	0.8	0.7	0.3	0.8	0.4*	0.4	1*	0.2	0.1	0.8
constr2	0			0.2								0.4	0	0.3	0.4	
round	0	0	0	0.8	0.2	0	0.1	0	0	0	0.7	0.3	0	0.1	0.1	0.1
nasal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
glottis1	0.8*	0.7*	0	0.8	0.9	0	0	0.8*	0.7*	0*	0.9	0.8	0,0	0.8*	0.9	0
glottis2	0.1			0.8*								0.8*		0.8	0.9	

The table does not include a complete set of parameters. We show those which we have found most useful in developing the computational model. To a certain extent the idea of a place/constriction centred characterisation comes from Browman and Goldstein [1986], but with different labels. Notice the distinction between place within the oral cavity (i.e. within the vowel place range – numerically indexed) and outside the oral cavity (place labels used).

The following table shows the relationship between our numerical system and a more traditional description using labels. Initial values assigned to the robustness parameter are also included, and all values are arguable: these are our first approximation working hypotheses.

place	lips, lips/teeth, 0.9 [teeth], 0.8 [front palate], 0.5 [mid palate], 0.1[back palate], velum, glottis
constriction	1 [stop], 0.9 [flap, tap], 0.8 [close fricative], 0.7 [open fricative], 0.5 [high], 0.3 [mid], 0.1 [low]
glottis	vowels: 1 (except [ə]: 0.7); liquids and semi-vowels: 0.8; voiced fricatives: 0.8; voiced plosives 0.8

robustness	stressed vowels: 0.9 (none); [ə] : 0.7 (voice);
	[p]: 0.9; other voiceless plosives: 0.5 (place);
	[b]: 0.7 (voice); other voiced plosives 0.3 (voice and place);
	lips and lips/teeth voiceless fricatives: voiceless: 0.9 (none); voiced: 0.7 (voice);
	oral fricatives: voiceless: 0.7 (place) 0.3 (voiced);
	semi-vowels: lips-teeth: 0.9; [l], [r] 0.9.
	(items in brackets are the vulnerable parameters)

In the extrinsic allophonic plan for this utterance there are eight candidate segments for coarticulation:

- [ˁb] – vocal cord vibration fails throughout the stop (aerodynamic failure: supraglottal pressure too high)
- [ə̊] – partial vocal cord vibration failure (common in unstressed vowels)
- [ɒ̹] – rounded (coarticulates with preceding rounded [w])
- [t̠̚] – retracted (coarticulates with preceding back [ɒ])
- [f̹] – rounded (coarticulates with the following rounded [ʊ]
- [ɫ̹] – rounded (coarticulates with preceding rounded [ʊ])
- [ˁr] – vocal cord vibration failure at start (aerodynamic failure: supraglottal pressure instability and pressure too high immediately following voiceless plosive [p] release)
- [ai] – the second pole ([i]) has greater than usual constriction – coarticulates with following [s]

At this point it is the job of the CPA to predict the normal intrinsic allophonic outcome of dynamically applying the appropriate coarticulatory rules as found on the phonetics tier's static plane. In traditional notation the coarticulated string would be: [$ ˁbə̊t̚ | wɒ̹t̠̚s ðə | ˈf̹ʊɫ̹ | pˁrais], and in matrix form would look like the following table. In some cells however we find by experiment that the predicted value gives way to a new value (highlighted). These are instances of CPA supervision to constrain normal coarticulatory processes. In the outline model presented in this paper this table represents the final gestural specification.

	b	ə	t̚	w	ɒ	t̚	s	ð	ə	ˈf̹	ʊ	ɫ	p	r	aɪ	s
type	bi–phasal	uni–polar	uni–polar	bi–phasal	uni–polar	uni–phasal	uni–polar	uni–polar	uni–polar	uni–polar	uni–polar	bi–polar	bi–phasal	bi–polar	bi–polar	uni–polar
rob	0.3	0.7	0.5	0.9	0.9	0.5	0.7	0.9	0.7	0.9	0.9	0.9	0.9	0.9	0.9	0.7
place1	lips	0.5	0.8*	lips	0.1	0.8 →0.6*	0.8*	teeth	0.5	lips/ teeth	0.2	0.2	lips	0.5	0.5	0.8*
place2	lips											0.2	lips	0.6	0.7	
constr1	1	0.3	1	0.5	0.2*	1	0.8	0.7	0.3	0.8	0.4*	0.4	1*	0.2	0.1	0.8
constr2	0			0.2								0.4	0	0.3	0.4 →0.5	
round	0	0	0	0.8	0.2 →0.5	0	0.1	0	0	0 →0.3	0.7	0.3 →0.5	0	0.1	0.1	0.1
nasal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
glottis1	0.8	0.7	0	0.8	0.9	0	0	0.8*	0.7*	0*	0.9	0.8	0,0	0.8	0.9	0

	→0,1*	→0.2*												→0*		
glottis2	0.1			0.8*								0.8*		0.8	0.9	

The CPA deals with coarticulation

The CPA now needs to address several questions concerning the predicted coarticulatory effects on the extrinsic allophonic utterance plan. Are any of these coarticulation effects likely to cause:

1. semantic ambiguity? – i.e. do any of the effects lead to phonemic changes which are not able to be repaired by general semantic context and which may result in ambiguity of meaning of the entire utterance? – NO
2. phonological ambiguity? – i.e. do any of the effects change the local meaning of any words? – NO

These two questions are relevant to *any* utterance. The answer *yes* on any occasion would prompt the CPA to attempt to minimise the ambiguities by constraining the predicted coarticulation effects. It would do this by supervising motor control to increase precision in the appropriate areas of the utterance. There is a general principle here: *Precision is lax so long as there is no predicted ambiguity.*

But now the CPA must deal with other input considerations:

1. Are there any intentional effects to be brought into the utterance? – on this occasion we have decided that the utterance is to be spoken carefully. The CPA knows that carefully – one of a number of possibilities it recognises – means a deliberateness of utterance reflecting increased precision and a somewhat slower tempo throughout the period in which authority is to be shown, i.e. the entire utterance in this case.
2. Are there any emotive effects for this utterance? – on this occasion, NO.

So the reasoning process conducted by the CPA continues: There are no serious ambiguities likely to be created by coarticulatory effects, but the utterance is to be spoken with generally increased precision and a reduction of the default tempo. Reduction of tempo itself will reduce the extent of coarticulation (since the phenomenon is tempo dependent: an increase in tempo correlates with increased coarticulation or failure of parameters depending on their robustness), though it may not eliminate coarticulation altogether. Increased precision of speech does not necessarily imply much reduction of coarticulation throughout the utterance. For us it would mean more careful supervision of the motor control – which may or may not result in reduced degrees of coarticulation. Coarticulation is a complex phenomenon: segment 'targets' are more likely to be hit with increased supervision of precision, but 'edge blending' (where a segment blends into the adjacent one) is never eliminated even in the slowest continuous speech.

The only effect we noted earlier was the tendency for the [t] of [wɒ̨t̠̚s] to be unreleased (because it preceded a same-place fricative) – a phonological rule in this speaker's accent. Authoritative speech will sometimes call for a change of accent (a phonological adjustment), or increased precision at the phonetic level (perhaps to *simulate* change of accent). Note that some accents are often considered to be spoken with more care or precision than others. In English it may be the case that Received Pronunciation is more carefully supervised than, say, Estuary English. We do not know if this is the case or not. But in this particular example we know that a full release of the [t] in this word can be managed at the phonetic level and can simulate a more careful accent normally handled at the phonological level. That is, this is not actually a local accent change (that would have been done earlier in the phonology), but an adjustment to the phonetics to simulate a phonological process. There is no doubt that there are a number of effects which can be both phonetic and phonological on this basis. Lateral or nasal releases of stops, for example, can often be similarly negated in favour of a ‛regular' release, giving rise to a perceived effect of more careful speech (e.g. [bɒtˡɫ] – laterally released [t] into the syllabic [ɫ]– vs. [bɒtɫ] – regular release into the syllabic [ɫ]; note, though, that if the [l] has been vocalised to [lᶷ] then [tˡ] is not a possibility).

CONCLUSION

We have presented an outline of a model of speech production which is specifically designed to account for a number of observations about speech and speakers. The model is fully computational, with particular attention paid to the choice of suitable paradigms for representing the different data structures involved. The model is multi-dimensional in the sense that it can be approached as a static representation of the inherent features of speech production in much the same way as early transformationalists approached the characterisation of syntax, or it can be seen as a dynamic system characterising the processes involved in time-governed production of individual utterances involving detailed properties such as expression.

We have incorporated the idea of supervision, particularly in the area of phonetic rendering of utterance plans. Phonetic rendering is a complex set of procedures involving a balance between the basic requirements of the utterance plan and a number of incoming pragmatic and other constraints. To achieve this we develop the idea of agent, particularly the Cognitive Phonetic Agent operating at the phonetic rendering level. An agent is an intelligent device able to evaluate competing requirements to optimise the balance between processes.

The paper has illustrated the model by dwelling on several data structures and showing how appropriate computational paradigms characterise them. A simple utterance has been traced through from its abstract phonemic representation to a fairly detailed intrinsic allophonic representation as an example to show how some of the stages in the computational model work.

Although by no means exhaustive or even completely accurate we feel that the model is currently coherent enough to be tested against samples of real speech. The errors and hypotheses generated by the testing procedure should feed naturally into an iterative process of refinement of the model.

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