Correlates of linguistic rhythm in the speech signal[☆]

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Abstract

Spoken languages have been classified by linguists according to their rhythmic properties, and psycholinguists have relied on this classification to account for infants' capacity to discriminate languages. Although researchers have measured many speech signal properties, they have failed to identify reliable acoustic characteristics for language classes. This paper presents instrumental measurements based on a consonant/vowel segmentation for eight languages. The measurements suggest that intuitive rhythm types reflect specific phonological properties, which in turn are signaled by the acoustic/phonetic properties of speech. The data support the notion of rhythm classes and also allow the simulation of infant language discrimination, consistent with the hypothesis that newborns rely on a coarse segmentation of speech. A hypothesis is proposed regarding the role of rhythm perception in language acquisition. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Speech rhythm; Prosody; Syllable structure; Language discrimination; Language acquisition; Phonological bootstrapping

1. Introduction

There is a clear difference between the prosody of languages such as Spanish or Italian on the one hand and that of languages like English or Dutch on the other.

Lloyd James (1940, cited by Pike, 1945) attributed this difference to rhythm and used the metaphor 'machine-gun rhythm' for the first group of languages and 'Morse code rhythm' for the second. In each group, different elements would recur at regular intervals establishing temporal organization: syllables in Spanish or Italian and stresses in English or Dutch. Pike (1945) thus renamed the two types of rhythms 'syllable-timed' and 'stress-timed', and Abercrombie (1967) went a step further by claiming that linguistic rhythm was either based on the isochrony of syllables, or on the isochrony of interstress intervals, for all languages throughout the world. Further work classified Germanic and Slavonic languages, as well as Arabic, as stress-timed, Romance languages as syllable-timed, and hypothesized a third category of mora-timed languages, including Japanese and Tamil (Abercrombie, 1967; Bertinetto, 1989; Port, Dalby & O'Dell, 1987; Ladefoged, 1975; Pike, 1945; Rubach & Booij, 1985; Steever, 1987).

Linguists are not the only ones who have committed themselves to these distinctions. Mehler, Dupoux, Nazzi and Dehaene-Lambertz (1996) relied on the syllable-timing/stress-timing dichotomy to explain how infants may learn part of the phonology of their native language. Indeed, they hypothesized that rhythm type should be correlated with the speech segmentation unit in any given language. That is, speakers of stress-timed languages should segment speech in feet, speakers of syllable-timed languages in syllables, and speakers of mora-timed languages in morae (Cutler, Mehler, Norris, & Segui, 1986; Otake, Hatano, Cutler, & Mehler, 1993; Mehler et al., 1996). Thus, precocious detection of the rhythm type of their native language might be a simple way for infants to decide which segmentation unit to use for further speech analysis (this view is further discussed in Section 5).

Furthermore, this hypothesis makes predictions for children exposed to a bilingual environment: if the two languages in question share the same segmentation unit, infants should have no trouble in selecting it; if the two languages do not, infants will be receiving contradictory input and should be confused, unless, of course, they are able to discriminate between the two languages without needing to segment speech: in this case they would be aware that two separate units are to be used. Mehler et al. (1996) therefore hypothesized that infants use rhythm to discriminate languages when they are exposed to languages of different rhythmic classes. This hypothesis is supported by the findings of Bahrick and Pickens (1988), Christophe and Morton (1998), Dehaene-Lambertz and Houston (1998), Mehler et al. (1988) and Moon, Cooper and Fifer (1993) who showed that young infants, including newborns (Mehler et al., 1988; Moon et al., 1993), can discriminate between sentences drawn from their mother tongue and sentences from a language belonging to another rhythmic class.[1] Moreover, in two of these studies (Dehaene-Lambertz & Houston, 1998; Mehler et al., 1988), discrimination was possible with low-pass filtered speech (at 400 Hz), highlighting the role of prosody.

Finally, the most convincing support for the 'rhythm-based language discrimina-

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[1] The pairs of languages tested were, respectively, French/Russian and English/Italian, English/Spanish, French/English, English/Japanese. Bosch and Sebastián-Gallés (1997) also showed that Spanish/Catalan discrimination was possible in 4-month-olds, but rhythm was not thought to be the critical cue.

tion hypothesis' is provided by Nazzi, Bertoncini and Mehler (1998), who showed, using filtered speech exclusively, that French newborns can discriminate between English and Japanese sentences, but not between Dutch and English ones. Moreover, they also showed that newborns can perform discrimination at the more abstract level of the rhythmic class: they discriminated a set of English and Dutch sentences from a set of Spanish and Italian ones, but failed to discriminate English and Spanish sentences from Dutch and Italian ones, strongly suggesting that rhythmic classes play a role in the infant's perception of speech.

Thus, it seems that the intuitions of the aforementioned phoneticians were right, and that the syllable-timing/stress-timing dichotomy may well be deeply anchored in the human perceptual system.

2. Current views on speech rhythm

2.1. Against the isochrony theory

Given the reasons just discussed for believing in rhythmic classes, one would expect that these groups of languages should differ by readily identifiable acoustic or phonetic parameters. However, this is not the picture provided by past studies on rhythm. A considerable amount of research has been carried out to assess the physical reality of the isochrony theory on syllable- and stress-timed languages. Nevertheless this research has failed to confirm the existence of different types of isochronous intervals in spoken language.

As far as stress-timed languages are concerned, it has been shown that the duration of interstress intervals in English is directly proportional to the number of syllables they contain (Bolinger, 1965; Lea, 1974; O'Connor, 1965; Shen & Peterson, 1962). Bolinger (1965) also showed that the duration of interstress intervals is influenced by the specific types of syllables they contain as well as by the position of the interval within the utterance. Interstress intervals thus do not seem to have a constant duration.

As to syllable-timed languages, Borzone de Manrique and Signorini (1983) have shown that in Spanish syllable duration is not constant and that interstress intervals tend to cluster around an average duration. Wenk and Wiolland (1982) did not find isochronous syllables in French. They rather proposed that larger rhythmic units–of the size roughly corresponding to the phonological phrase in prosodic phonology– are responsible for rhythm in French.

A study was also carried out involving six languages, of which, according to Abercrombie (1967), three are classified as syllable timed–French, Telegu and Yoruba–and three as stress timed–Arabic, English and Russian (Roach, 1982). The results of this research are (a) that variation in syllable duration is similar in all six languages and (b) that stress pulses are not more evenly spaced in the second group of languages than they are in the first one.

Similar work by Dauer (1983) with English (stress-timed), and Spanish, Italian and Greek (syllable-timed) suggests that (a) the mean duration of interstress inter-

vals for all the analyzed languages is proportional to the number of syllables in the interval, (b) stresses do not recur more regularly in English than they do in the other languages.

The studies mentioned above do not lead us to adhere to a strict theory of isochrony. The subjective perception of isochrony, if real, must therefore be based on a more abstract construct, possibly similar to that which governs the relation between underlying beats and surface rhythm in music (Cooper & Meyer, 1960; Lerdahl & Jackendoff, 1983; see also Drake & Palmer, 1993).

2.2. A new account of speech rhythm

A view of rhythm radically different from that of Abercrombie (1967) and Pike (1945), among others, was first proposed by Dasher and Bolinger (1982), according to whom the impression of different types of rhythm is the result of specific phonological phenomena in a given language. The distinction between syllable-timed and stress-timed languages would thus not be a primitive of phonology, but rather a product of their respective phonological properties.

Dauer (1983) observed that stress-timed and syllable-timed languages have a number of different distinctive phonetic and phonological properties, of which the two most important are:

- Syllable structure: stress-timed languages have a greater variety of syllable types than syllable-timed languages. As a result, they tend to have heavier syllables.[2] In addition, this feature is correlated with the fact that in stress-timed languages, stress most often falls on the heaviest syllables, while in syllable-timed languages stress and syllable weight tend to be independent.
- Vowel reduction: in stress-timed languages, unstressed syllables usually have a reduced vocalic system (sometimes reduced to just one vowel, schwa), and unstressed vowels are consistently shorter, or even absent (this was also noticed by Bertinetto, 1981).

These features combine with one another to give the impression that some syllables are far more salient than others in stress-timed languages, and that all syllables tend to be equally salient in syllable-timed languages. This in turn, creates the impression that there are different types of rhythm.

In addition, Dauer (1987) suggested that the different properties mentioned above could be independent and cumulative: a language should not be thought to be either stress-timed or syllable-timed with the corresponding properties; rather, the more properties typical of stress-timed languages a language presents, the more it is stress-timed, and the less it is syllable-timed. Dauer (1987) thus advocated a continuous uni-dimensional model of rhythm, with typical stress-timed and syllable-timed

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[2] This relies on the assumption that the syllable inventory of a language always starts with the most simple syllables (with the exception of V which is not legal in all languages). We are not aware of any language that would have complex syllables without having the simpler ones, and this is indeed excluded by phonological theories (see for example Blevins, 1995).

languages at either end of the continuum. Henceforth we will refer to this position as to the phonological account of rhythm.

2.3. Existence of intermediate languages

Nespor (1990) supported this view with critical examples, arguing that indeed, there are languages whose features match neither those of typical stress-timed languages, nor those of typical syllable-timed languages. Even though they have most often been described as syllable-timed and stress-timed, respectively, Catalan and Polish are such languages. Indeed, Catalan has the same syllabic structure and complexity as Spanish, and thus should be syllable-timed, but it also presents the vowel reduction phenomenon, which is consistently associated with stress-timed languages. Polish presents the opposite configuration, namely, a great variety of syllable types and high syllabic complexity, like stress-timed languages, but no vowel reduction at normal speech rates. Thus these two languages would rate as intermediate on a rhythmic scale like the one proposed by Dauer (1987). As a matter of fact, phonologists did not reach any firm agreement on their rhythmic status (Hayes & Puppel, 1985; Mascaró, 1976; Rubach & Booij, 1985; Wheeler, 1979).

It should be noticed that while Dauer (1987) proposed that languages may be scattered along a continuum, the fact that some languages fall between typically syllable-timed and stress-timed languages does not exclude the possibility that there are just more classes than those originally proposed. For instance, it has been proposed that twelve inventories of possible syllable types can be grouped into five classes according to their markedness (Levelt & van de Vijver, 1998). Three of these classes seem to correspond to the three rhythmic classes described in the literature. It might very well be that the other two classes–both containing less studied languages–have characteristic rhythms, pointing to the possibility that there are more rhythmic classes rather than a continuum.

Which of the two versions turns out to be correct is an empirical question which can be answered only after many more languages belonging to unrelated families are investigated.

2.4. Perspectives

Dauer (1987) draws the conclusion that a language cannot be assigned to one or the other rhythmic class on the basis of instrumental measurements of interstress intervals or syllable durations. This suggests that we should look for more effective measurements to account for the perception of speech rhythm. While the phonological account appears to be adequate, it does not explain how rhythm is extracted from the speech signal by the perceptual system.

Indeed, a purely phonological model of rhythm fails to make a number of predictions. As we mentioned above, infants' behavior is consistent with the hypothesis that they discriminate languages on the basis of the stress-timed/syllable-timed dichotomy. However, unsurprisingly, only well-classified languages have been used in these experiments. How would infants classify languages such as Polish

or Catalan? The phonological model cannot answer this question because it is not implemented. It does not explicitly situate these languages with respect to each other on the rhythm scale, and it does not say how much each phonological property contributes to the perception of rhythm, and how properties interact with each other. As a result, it is impossible to predict whether Polish is in the middle of the continuum or, say, whether its syllabic complexity overrides its lack of vowel reduction and pushes it towards the stress-timed end. Answers to these questions are necessary, if we are to understand how infants perceive speech rhythm, how they learn the phonology of their native language, and how they can deal with any kind of bilingual environment.

In the remainder of this paper, we propose an implementation of the phonological account of speech rhythm with the aim of clarifying how rhythm may be perceived and to make predictions as to how listeners classify languages according to their rhythm.

3. Instrumental measurements in eight languages

3.1. Rationale

Dauer (1987) observes that instrumental and phonological studies must first decide where the stresses fall and what a syllable is in a specific language, because neither 'syllable' nor 'stress' have general phonetic definitions.

Since our main interest is to explain how infants come to perceive contrasting rhythms at birth, and since the infant cannot be expected to know anything specific a priori about the language to be learned, we would like to argue that a viable account of speech rhythm should not rely on complex and language-dependent phonological concepts. We will therefore attempt to provide a purely phonetic definition of language rhythm without appealing to those concepts.

Our starting point is a hypothesis about the perception of speech by the infant. Following Mehler et al. (1996), we propose that infant speech perception is centered on vowels, because these have more energy and last longer than most consonants. Vowels also carry accent and signal whether a syllable is strong or weak. In addition, there is evidence that newborns pay more attention to vowels than to consonants (Bertoncini, Bijeljac-Babic, Jusczyk, Kennedy, & Mehler, 1988), and that they are able to count the number of syllables (and therefore vowels) in a word, independently of syllable structure or weight (Bertoncini & Mehler, 1981; Bertoncini, Floccia, Nazzi, & Mehler, 1995; Bijeljac-Babic, Bertoncini, & Mehler, 1993; van Ooyen, Bertoncini, Sansavini, & Mehler, 1997).

We thus assume that the infant primarily perceives speech as a succession of vowels of variable durations and intensities, alternating with periods of unanalyzed noise (i.e. consonants), or what Mehler et al. (1996) called a Time-Intensity Grid Representation (TIGRE).

Guided by this hypothesis, we will attempt to show that a simple segmentation of speech into consonants and vowels can:[3]

- Account for the standard stress- /syllable-timing dichotomy and investigate the possibility of other types of rhythm;
- account for language discrimination behaviors observed in infants;
- clarify how rhythm might be extracted from the speech signal.

3.2. Material

Sentences were selected from a multi-language corpus initially recorded by Nazzi et al. (1998) and to which Polish, Spanish and Catalan were added for the present study.[4] Eight languages (English, Dutch, Polish, French, Spanish, Italian, Catalan, Japanese), four speakers per language and five sentences per speaker were chosen, constituting a set of 160 utterances. Sentences were short news-like declarative statements, initially written in French, and loosely translated into the target language by one of the speakers. They were matched across languages for the number of syllables (from 15 to 19), and roughly matched for average duration (about 3 s). Sentences were read in a soundproof booth by female native speakers of each language, digitized at 16 kHz and recorded directly on a hard disk.

3.3. Method

The first author marked the phonemes of each sentence with a sound-editing software, using both auditory and visual cues. Segments were identified and located as precisely as possible, using the phoneme inventory of each language.

Phonemes were then classified as vowels or consonants. This classification was straightforward with the exception of glides, for which the following rule was applied: Pre-vocalic glides (as in English /kwiːn/ ''queen'' or /vawəl/ ''vowel'') were treated as consonants, whereas post-vocalic glides (as in English /haw/ ''how'') were treated as vowels.

Since we made the simplifying assumption that the infant only has access to the distinction between vowel and consonant (or vowel and other), we did not measure the durations of individual phonemes. Instead, within each sentence we measured the duration of *vocalic* and *consonantal intervals*. A vocalic interval is located between the onset and the offset of a vowel, or of a cluster of vowels. Similarly, a consonantal interval is located between the onset and the offset of a consonant, or of a cluster of consonants. The duration of vocalic and consonantal intervals adds up to the total duration of the sentence.

As an example, the phrase 'next Tuesday on' (phonetically transcribed as /

Table 1

Total number of measurements, proportion of vocalic intervals (%V), standard deviation of vocalic intervals over a sentence (ΔV), standard deviation of consonantal intervals over a sentence (ΔC), averaged by language, and their respective standard deviations[a]

Languages	Vocalic intervals	Consonantal intervals	%V (SD)	ΔV (SD) ($\times 100$)	ΔC (SD) (*100)
English	307	320	40.1 (5.4)	4.64 (1.25)	5.35 (1.63)
Polish	334	333	41.0 (3.4)	2.51 (0.67)	5.14 (1.18)
Dutch	320	329	42.3 (4.2)	4.23 (0.93)	5.33 (1.5)
French	328	330	43.6 (4.5)	3.78 (1.21)	4.39 (0.74)
Spanish	320	317	43.8 (4.0)	3.32 (1.0)	4.74 (0.85)
Italian	326	317	45.2 (3.9)	4.00 (1.05)	4.81 (0.89)
Catalan	332	329	45.6 (5.4)	3.68 (1.44)	4.52 (0.86)
Japanese	336	334	53.1 (3.4)	4.02 (0.58)	3.56 (0.74)

[a] ΔV, ΔC and their respective SDs are shown multiplied by 100 for ease of reading.

nεkstjudeiɔn/) has the following vocalic and consonantal intervals: /n/ /ε/ /kstj/ /u/ /zd/ /eiɔ/ /n/.

From these measurements we derived three variables, each taking one value per sentence:

- the proportion of vocalic intervals within the sentence, that is, the sum of vocalic intervals divided by the total duration of the sentence ($\times 100$ in Table 1), noted as %V.
- the standard deviation of the duration of vocalic intervals within each sentence, noted as ΔV.
- the standard deviation of the duration of consonantal intervals within each sentence, noted as ΔC.[5]

3.4. Results

Table 1 presents the number of measurements, the average proportion of vocalic intervals (%V), and the average standard deviations of consonantal (ΔC) and vocalic (ΔV) intervals across all sentences of each language. Languages are ordered depending on %V. As can be seen, they also seem to be ordered from most to least stress-timed, which is a first indication that these measurements reflect something about rhythmic structure.

It is now possible to locate the different languages in a three-dimensional space. Figs. 1–3 show the projections of the data on the (%V, ΔC), (%V, ΔV) and (ΔV, ΔC) planes. The (%V, ΔC) projection clearly seems to fit best with the standard rhythm classes. How reliable is this account? We computed an ANOVA by introducing the 'rhythm class' factor (Polish, English and Dutch as stress-timed, Japanese as mora-

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[5] Note that %C is isomorphic to %V, and thus needs not be taken into consideration.
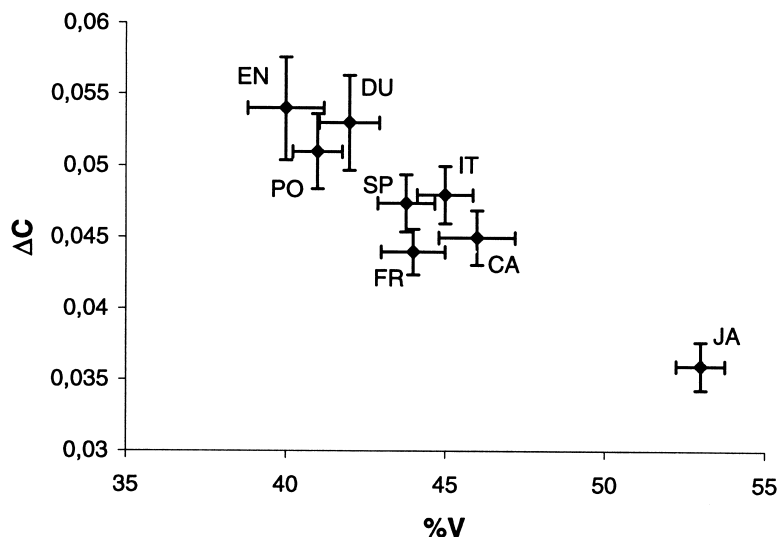
Fig. 1. Distribution of languages over the (%V, ΔC) plane. Error bars represent ± 1 standard error.

timed and the rest as syllable-timed). For both %V and ΔC, there was a significant effect of rhythm class ($P < 0.001$). Moreover, post-hoc comparisons with a Tukey test showed that each class was significantly different from the two others, both in %V (each comparison $P < 0.001$) and ΔC ($P \leq 0.001$). No significant class effect was found with ΔV.

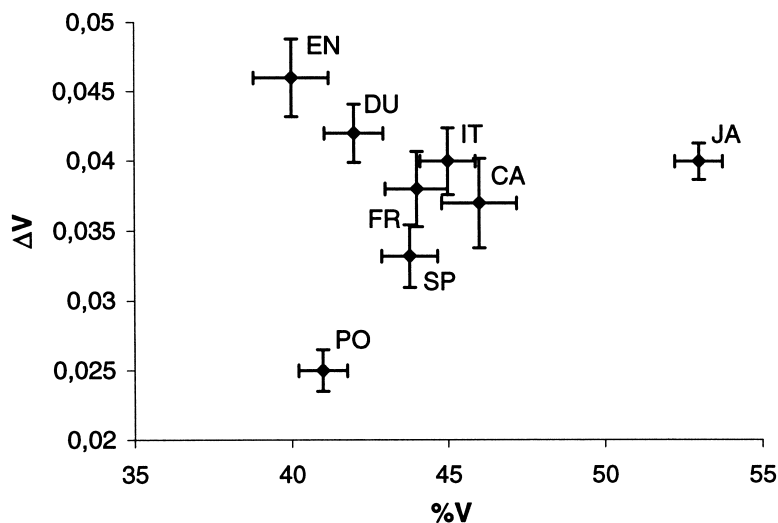Thus %V and ΔC both seem to support the notion of stress-, syllable- and mora-

Fig. 2. Distribution of languages over the (%V, ΔV) plane. Error bars represent ± 1 standard error.
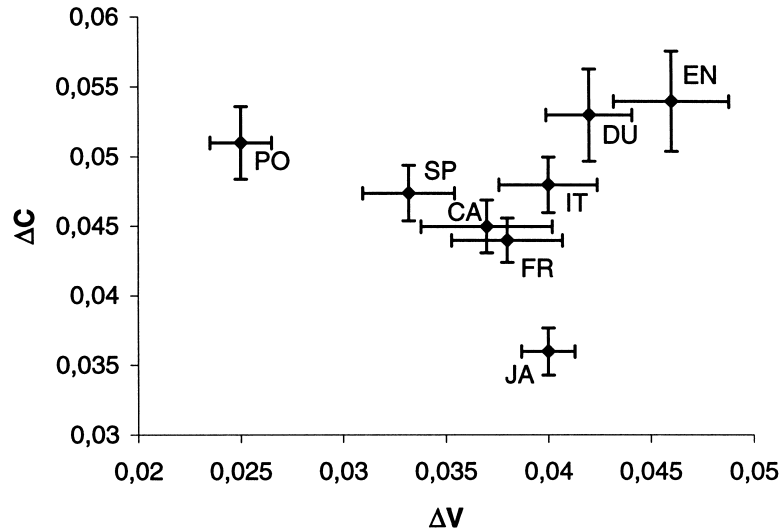
Fig. 3. Distribution of languages over the (ΔV, ΔC) plane. Error bars represent ± 1 standard error.

timed languages. However, ΔV suggests that there may be more to speech rhythm than just these distinctions; this variable, although correlated with the two others, rather emphasizes differences between Polish and the other languages. We will come back to this point further below.

3.5. Discussion

As mentioned earlier, this study is meant to be an implementation of the phonological account of rhythm perception. The question now is whether our measurements can be related to specific phonological properties of the languages.

ΔC and $\%V$ appear to be directly related to syllabic structure. Indeed, a greater variety of syllable types means that some syllables are heavier (see Footnote 2). Moreover in most languages, syllables gain weight mainly by gaining consonants. Thus, the more syllable types a language instantiates, the greater the variability in the number of consonants and in their overall duration in the syllable, resulting in a higher ΔC. This also implies a greater consonant/vowel ratio on average, i.e. a lower $\%V$ (hence the evident negative correlation between ΔC and $\%V$). It is therefore not surprising to find English, Dutch and Polish (more than 15 syllable types) at one end of the ΔC and $\%V$ scales, and Japanese (four syllable types) at the other. Thus, the nice fit between the ($\%V$, ΔC) chart and the standard rhythm classes comes as an empirical validation of the hypothesis that rhythm contrasts are accounted for by differences in the variety of syllable structures.

Apparently the ΔV scale cannot be interpreted as transparently as ΔC, since at least the following phonological factors combine with each other and influence the variability of vocalic intervals:

- Vowel reduction (English, Dutch, Catalan);
- contrastive vowel length (Japanese);
- vowel lengthening in specific contexts (Italian);
- long vowels (tense vowels and diphthongs in English and Dutch, nasal vowels in French).

Only vowel reduction and contrastive vowel length have been described as factors influencing rhythm (Dauer, 1987), but the present analysis suggests that the other factors may also play a role. In our measurements, ΔV reflects the sum of all phenomena. As a possible consequence, the ΔV scale seems less related to the usual rhythm classes. Yet, the two languages with the lowest ΔV, Spanish and Polish, are the ones which show none of the above phenomena that are likely to increase the variability of vocalic intervals. Thus ΔV still reflects phonological properties of languages, but it remains an empirical question whether it tells us something about rhythm perception. This may be assessed on the basis of Polish.

Polish, in fact, appears related to the stress-timed languages on the ($\%V$, ΔC) chart. However, on the ΔV dimension, it becomes clearly different from English and Dutch. This finding echoes the doubts raised by Nespor (1990) about its actual status and suggests that indeed, Polish should be considered neither stress- nor syllable- (nor mora-) timed. At this stage, new discrimination experiments are clearly needed to test whether ΔV plays a role in rhythm perception.

4. Confrontation with behavioral data

Following Dasher and Bolinger (1982) and Dauer (1983), we have assumed that the standard rhythm classes postulated by linguists arise from the presence and interaction of certain phonological properties in languages. Moreover, we have shown that these phonological properties have reliable phonetic correlates that can be measured in the speech signal, and that these correlates predict the rhythm classes. It follows that at least some rhythmic properties of languages can be extracted by phonetic measurements on the signal, and this finding allows us to elaborate a computational model of how different types of speech rhythm may be retrieved by the perceptual system. That is, we assume that humans segment utterances into vocalic and consonantal intervals, compute statistics such as $\%V$, ΔC and ΔV, and associate distinct rhythm types with the different clusters of values. But could we really predict which pairs of languages can and which cannot be discriminated on the basis of rhythm? At first glance one might be tempted to say that the ($\%V$, ΔC) chart predicts discrimination between rhythm classes, as previously hypothesized. However, specific predictions crucially depend on how much overlap there is between the different languages, and on how large the sets of sentences are (the larger, the shorter the confidence intervals for each language). As we will see below, the discrimination task that is used in a particular experiment can also play a role.

4.1. Adults

4.1.1. Language discrimination results

Unlike newborns, adults can be expected to use a broad range of cues to categorize sentences from two languages: possibly rhythm, but also intonation, segmental repertoire and phonotactics, recognition of known words, and more generally, any knowledge or experience related to the target languages and to language in general. In order to assess the adults' ability to discriminate languages on the basis of rhythm alone, it is thus crucial to prevent subjects from using any other cues.

There are practically no studies on adults that have fulfilled this condition. A few studies have tried to degrade the stimuli in order to isolate prosodic cues: Bond and Fokes (1991) superimposed noise onto speech to diminish non-prosodic information. Others have managed to isolate intonation by producing a tone following the fundamental frequency of utterances (de Pijper, 1983; Maidment, 1976, 1983; Willems, 1982). Ohala and Gilbert (1979) added rhythm to intonation by modulating the tone with the envelope of utterances. Dehaene-Lambertz (1995), den Os (1988) and Nazzi (1997) used low-pass filtered speech. Finally, Ramus and Mehler (1999) used speech resynthesis and manipulated both the phonemes used in the synthesis and F0.

Among all these studies, only den Os (1988) and Ramus and Mehler (1999) have used stimuli that are as close as one can get to pure rhythm. Den Os rendered the utterances monotone ($F0 = 100$ Hz) by means of LPC synthesis and then performed low-pass filtering at 180 Hz. Ramus and Mehler resynthesized sentences where consonants were all replaced by /s/, vowels by /a/, and F0 was made constant at 230 Hz. However, whereas Ramus and Mehler did not disclose the target languages and tried to make it impossible for the subjects to use any other cue than rhythm, den Os tried to cue them in various ways: subjects were native speakers of one of the target languages (Dutch), and the auditory stimuli were also presented in written form, thus making the evaluation of the correspondence between the rhythm of the stimuli and their transcription possible. Therefore we cannot consider that den Os' experiments assess discrimination on the basis of rhythm alone. The only relevant results for our present purpose are thus those of Ramus and Mehler (1999), showing that French subjects can discriminate English and Japanese sentences on the basis of rhythm only, without any other cues.

4.1.2. Modeling the task

Ramus & Mehler trained subjects to categorize 20 English and Japanese sentences uttered by two speakers per language. They then tested the subjects on 20 new sentences uttered by two new speakers.

This procedure is formally analogous to a logistic regression. Given a numerical predictor variable *V* and a binary categorical variable *L* over a number of points, this statistical procedure finds the cut-off value of *V* that best accounts for the two values of *L*. The procedure can be applied to one half of the existing data (training phase), and the cut-off value thus determined can be used to predict the values of *L* on the other half of the data (test phase).

Here, we take language, restricted to the English/Japanese pair, as the categorical

variable, and %*V* as the numerical variable. %*V* rather than Δ*C* is chosen because it presents less overall variance. Ten sentences of each language, uttered by two speakers per language, are used as the training set, and the ten remaining sentences per language, uttered by other speakers, are used as the test set. The simulation thus includes the same number of sentences as the behavioral experiment. In addition, sentences used in the experiment and the simulation are drawn from the same corpus, uttered by the same speakers, and there even is some overlap between the two.

4.1.3. Results

4.1.3.1. English/Japanese   We find that the regression coefficients calculated on the 20 training sentences can successfully classify 19 of them, and 18 of the 20 test sentences (90% hit rate in the test phase). To assess any asymmetry between the training and the test sets, we redid the regression after exchanging the two sets, and we obtain a 95% hit rate in the test phase (chance is 50%). This analysis shows that it is possible to extract enough regularities (in terms of %*V*) from 20 English and Japanese sentences to be able to subsequently classify new sentences uttered by new speakers, thus simulating the performance of Ramus & Mehler's subjects.

Furthermore, since we chose our 20 sentences from the same corpus as Ramus & Mehler, there is a substantial overlap between the sentences of the experiment and those of the simulation (26 sentences out of 40). It is thus possible to compare the subjects' and the simulation's performance for those sentences. Of the three sentences that are misclassified in the simulation, two were used in the experiment. It appears that these are the very two sentences that were most misclassified by subjects as well, yielding 38 and 43% correct classification, respectively, meaning that subjects classified them more often as Japanese than as English. This similarity between the experimental results and the simulation is striking, but it rests on two sentences only.

To push the comparison further, the 26 sentences used in both the experiment and the simulation are plotted in Fig. 4, showing their %*V* value against the proportion of subjects correctly classifying each of them. This figure first shows the almost perfect separation of English and Japanese sentences along the %*V* dimension, thus explaining the high level of classification in the simulation. More interestingly, it appears that the lower the %*V* value of an English sentence, the better it is classified by subjects, as shown by a linear regression ($R = -0.87$, $P < 0.001$). Such a correlation is not apparent for Japanese ($R = -0.11$, N.S.). Notice, however, that Japanese sentences present less variance in %*V*, and tend to be well-classified as a whole, except for one sentence, which has indeed the lowest %*V* among Japanese sentences.

This correspondence between %*V* and the subjects' classification scores provides evidence for the psychological plausibility of the proposed model: The results suggest that subjects actually compute %*V*, and base their English/Japanese decision at a value of approximately %*V* = 0.46. Moreover, the data show an interpretable distance effect on English sentences, the ones having a %*V* further from the decision threshold being easier to classify. Why would Japanese sentences not show such an
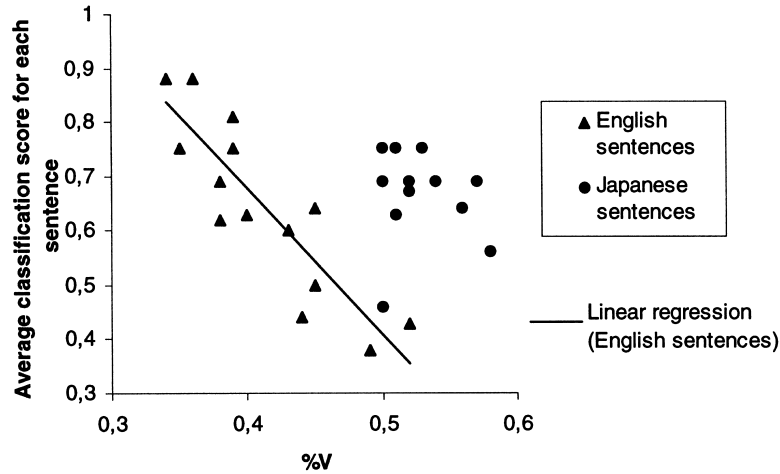
Fig. 4. English/Japanese discrimination in adults. Average classification scores for individual sentences across subjects, plotted against their respective *%V* values.

effect? Apart from the smaller variance which reduces the probability of observing the effect, we may conjecture that variation in *%V* among English sentences reflects differences in syllable complexity, whereas among Japanese sentences it may reflect differences in vowel length. Since vowel length is not contrastive in French, the French subjects in Ramus and Mehler (1999) may have been less sensitive to these differences.

4.1.3.2. Other pairs of languages   Obviously, the classification scores presented in the previous section are much higher in the simulation than in the experiment (68% in the test phase). This is due to the fact that the logistic regression finds the best possible categorization function for the training set, whereas human subjects fail to do so, even after three training sessions (mean classification score after first training session: 62.5%).

This discrepancy may let one think that the logistic regression predicts the discrimination of many more pairs of languages than are actually discriminated by subjects. Since few behavioral results are available, we made a simulation for all other pairs of languages presented in this paper to predict future discrimination experiments on adult subjects.

For all the pairs of languages, the predictor variable was *%V*, and the regression was performed twice, exchanging the training set and the test set to avoid asymmetries. The classification score reported in Table 2 is the average of the two scores obtained in the test phase.

As can be seen in Table 2, we do not predict that all pairs of languages will be discriminated; high scores are found only when Japanese is contrasted with another language. Moreover, the pattern of scores conforms to the rhythm classes,[6] that is, discrimination scores are always higher between classes (60% or more) than within

Table 2
Simulation of adult discrimination experiments for the 26 pairs of languages[a]

	English	Dutch	Polish	French	Italian	Catalan	Spanish
Dutch	57.5						
Polish	50	57.5					
French	60	60	65				
Italian	65	62.5	65	55			
Catalan	65	62.5	65	57.5	35		
Spanish	62.5	57.5	62.5	50	50	37.5	
Japanese	92.5	92.5	95[b]	90	90	87.5	95[b]

[a] Scores are classification percentages on the test sentences obtained from logistic regressions on the training sentences. %V is the predictor variable. Chance is 50%.

[b] In these cases one of the two regressions failed to converge, meaning that the solution of the regression was not unique. This happens when the predictor variable completely separates the sentences of the two languages (100% classification on the training set). Only the classification percentage of the regression that converged is reported in the table.

class (less than 60%), with only one exception, i.e. that of Dutch/Spanish (between class, 57.5%). We know of no behavioral result or prediction regarding this pair, but this prediction remains an oddity within the rhythm classes framework.

These simulations provide quantitative predictions regarding the proportion of sentences an adult subject may be expected to correctly classify in a language discrimination task, assuming the subject has a measure of speech rhythm equivalent to %V. We hope to gather more behavioral results to compare with these predictions.

4.2. Infants

4.2.1. Language discrimination results

There are numerous reports in the literature of language discrimination experiments with infant subjects of different ages and linguistic backgrounds, using various language pairs and types of stimuli. Table 3 only presents results obtained with newborns, because additional factors affect the behavior of older babies. Indeed, 2-month-old infants seem to discriminate only between native and foreign languages (Christophe & Morton, 1998; Mehler et al., 1988). Moreover, there is evidence that after that age infants can perform the discrimination using cues other than rhythm, presumably intonation, and phonetics or phonotactics (Christophe & Morton, 1998; Guasti, Nespor, Christophe, & van Ooyen, in press; Nazzi, Jusczyk & Johnson, submitted). Of all the results obtained with newborns, one only is not considered here, French/Russian, since we do not have Russian in our corpus.

It should be noted that experiments on infants have not demonstrated discrimination based on rhythm only, since the stimuli used always preserved other types of

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[6] It should be noted that the scores given for Catalan/Italian and Catalan/Spanish (35 and 37.5%, respectively) do not reflect discrimination through mislabeling. They rather suggest that these pairs are so close that there may be more important rhythmic differences between some speakers than between the languages.

Table 3
Language discrimination results in 2–5-day-old infants

Language pair	Discrimination	Stimuli	Reference
French/Russian	Yes	Normal and filtered[a]	(Mehler et al., 1988)
English/Italian	Yes	Normal	(Mehler et al., 1988; see re-analysis by Mehler et al., 1995)
English/Spanish	Yes	Normal	(Moon et al., 1993)
English/Japanese	Yes	Filtered[a]	(Nazzi et al., 1998)
English/Dutch	No	Filtered[a]	(Nazzi et al., 1998)
Dutch/Japanese	Yes	Resynthesized[b]	Ramus et al., in preparation
Spanish/Catalan	No	Resynthesized[b]	Ramus et al., in preparation
English + Dutch vs. Spanish + Italian	Yes	Filtered[a]	(Nazzi et al., 1998)
English + Spanish vs. Dutch + Italian or English + Italian vs. Dutch + Spanish	No	Filtered[a]	(Nazzi et al., 1998)

[a] Stimuli were low-pass filtered at 400 Hz.
[b] Stimuli were resynthesized in such a manner as to preserve only broad phonotactics and prosody (see Ramus & Mehler, 1999).

information. The hypothesis that newborns base their discrimination on speech rhythm only relies on the pattern of discriminations found across the different pairs of languages. This pattern is indeed consistent with the standard rhythm classes. Success of our simulations to predict this very pattern would thus confirm the feasibility, and therefore the plausibility, of rhythm-based discrimination.

4.2.2. The discrimination task

Discrimination studies with infants report two kinds of behavior: firstly, recognition and/or preference for maternal language, and secondly, discrimination between unfamiliar languages. The first supposes that infants are already familiar with their maternal language, i.e. that they have formed a representation of what utterances in this language sound like. It is with this representation that utterances from an unfamiliar language are compared. Discrimination of unfamiliar languages does not suppose familiarization prior to the experiment. It requires, however, familiarization with one language during the experiment, as is the case in habituation/dishabituation procedures. Infants then exhibit recovery of the behavioral measure (dishabituation) when the language changes.

Thus, in both cases, discrimination behavior involves forming a representation of one language, and comparing utterances from the new language with this representation. Discrimination occurs when the new utterances do not match the earlier representation. However, neither standard comparisons between sets of data nor procedures involving supervised training (like the logistic regression) can

adequately model the infant's task, since they presuppose a priori two categories, whereas infants react spontaneously to a change in category. Actually, we cannot even assert that the infant forms two categories.

Here, we will try and model as closely as possible the infant's task as it occurs in non-nutritive sucking discrimination experiments such as those of Nazzi, Bertoncini and Mehler (1998). For this purpose we will model infants' representation of sentences rhythm, their representation of a language, and their arousal in response to sentences. We will then simulate experiments, by simulating subjects divided into an experimental and a control group, a habituation and a test phase, and sentences drawn in a random order.

4.2.3. A model of the task

An experiment unfolds in a number of steps (indexed as n), each consisting of the presentation of one sentence. The rhythm of each sentence S_n heard by the infant at step n is represented as its $\%V_n$ value. In the course of an experiment, the infant forms a prototypical representation P_n of all sentences heard. Here this prototype is taken as the average $\%V$ of all the sentences heard so far[7]

$$P_n = \frac{1}{n} \sum_{i=1}^{n} \%V_i$$

The infant has a level of arousal A_n, which is modulated by stimulation and novelty in the environment. In the experiment, all things being equal, arousal is dependent on the novelty of the sentences heard. For the simulation, we take as arousal level the distance between the last sentence heard and the former prototype. That is, at step n, $A_n = |\%V_n - P_{n-1}|$. We further assume that there is a causal link and a positive correlation between arousal and sucking rates observed in the experiments, that is, a rise in arousal causes a rise in sucking rate. Given this assumption, we do not model the link between arousal and sucking rate, and we assess the subject's behavior directly through arousal.

The simulation of a discrimination experiment for a given pair of languages involves:

- The simulation of 40 subjects, divided into two groups: experimental (language and speaker change), and control (same language, speaker change). The order of appearance of languages and speakers is counterbalanced across subjects. Subjects belonging to the same counterbalancing subgroup only differ with respect to the order of the sentences heard within a phase (individual variability is not modeled).
- For each subject:
  - In the habituation phase, ten sentences uttered by two speakers in the habitua-

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[7] A more realistic model could implement a limited memory, storing, say, the last ten sentences. Here, as the number of sentences is low anyway (ten in each phase), this would hardly make a difference.

tion language are presented in a random order. P_n and A_n are calculated at each step.
- Automatic switch to the test phase after ten habituation sentences.
- In the test phase, ten new sentences uttered by two new speakers in the test language are presented in a random order. P_n and A_n are calculated at each step.

- Comparison of arousal pattern between the experimental and control groups.

There are important differences between the proposed simulations and the real experiments that deserve to be discussed. Firstly, in the experiments, switch to the test phase follows reaching a certain habituation criterion, namely, a significant decrease in the sucking rates. This is to ensure (1) that the switch occurs at a comparable stage of every infant's sucking pattern, (2) that infants have the possibility to increase their sucking again after the switch, and thus to show dishabituation. Here, these conditions serve no purpose, because they only address the link between arousal and the sucking behavior, which we do not model. In the simulations, after presentation of the ten habituation sentences in a given language, all the subjects have reached the same state: their prototype P_{10} is just the average of the %V values of the 10 sentences, and it will not be significantly modified by presenting the same sentences again until a habituation criterion is met, as is done in the real experiments. Secondly, in most experiments, more samples of speech in each language are used than in the simulation. In Nazzi, Bertoncini and Mehler (1998), for instance, 40 sentences per language were used, while here we have only 20. However, discrimination between Dutch and Japanese was also shown in newborns using only 20 sentences per language (Ramus et al., in preparation), suggesting that 20 sentences are enough for babies to reliably represent and discriminate two languages. If anything, using 20 sentences only rather than 40 should reduce the probability of observing a significant discrimination in the simulation, since more sentences would lead to more accurate prototypes at the end of the habituation phase.

4.2.4. Results
Simulations are run on all 28 pairs of languages studied in this paper. Discrimination is assessed by testing whether arousal in the experimental group is higher than in the control group during the test phase.[8] The dependent variable is the average arousal level over the 10 test sentences

$$\left(\frac{1}{10} \sum_{n=11}^{20} A_n \right)$$

and the factor is group. We use a non-parametric Mann–Whitney test because we have no hypothesis on the distribution of arousal levels. Significance levels of this

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[8] As we have explained in the preceding section, both groups have attained the same average prototype at the end of the habituation. It is thus not necessary to take into account the arousal level at the end of the habituation, through a subtraction or a covariance analysis, as is done when analyzing sucking experiments. In the present case, such a procedure could only add more noise to the analysis.

test for all the simulations are presented in Table 4. As presented, these levels are directly comparable to each other, since the tests are computed on the same type of data and with the same number of subjects (40).

Four language pairs (marked by the letter C in the table) present a peculiar arousal pattern, in that in the test phase the control group has a higher average arousal than the experimental group, reaching significance in the case of Catalan/Italian. This should not, however, be interpreted as predicting a discrimination. These four pairs concern syllable-timed languages that are very close to each other. Because the average differences between these languages are so small, they can even be smaller than speaker differences within the same language (recall that the control group switches from two speakers to two other speakers of the same language). As a consequence, the four corresponding P-values in Table 4 should be correctly interpreted: the Mann–Whitney test performed being two-tail, the P-values represent the probability of accepting the null hypothesis (i.e. experimental $=$ control). However, a discrimination is predicted only when the alternative hypothesis (experimental $>$ control) is accepted.

In order to better visualize the data, we present arousal curves for three representative pairs of languages. The figures show mean arousal values at each step of the simulation for the experimental and control groups. Note that arousal is not defined at step 1 ($A_1 = |\%V_1 - P_0|$ and P_0 is not defined), and therefore is not shown on the charts. Switch from the habituation to the test phase occurs between steps 10 and 11. Fig. 5 shows arousal curves for the English/Japanese simulation, Fig. 6 for English/Spanish, and Fig. 7 for Spanish/Italian, illustrating a large, a moderate, and a null discrimination effect, respectively.

It appears that the simulations can successfully predict the results of all the behavioral data available (shown in boldface in Table 4). Moreover, they are highly consistent with the rhythm class hypothesis. Only two pairs of languages do not conform to this pattern: Polish/French and Spanish/Dutch, for which no discrimination is predicted by the simulation. It is interesting to note that in simulations of adult experiments, a relatively low classification score was already predicted for Spanish/Dutch, though not for Polish/French. Although no existing behavioral result is in

Table 4
Simulation of infant discrimination experiments for the 26 pairs of languages[a,b]

	English	Dutch	Polish	French	Italian	Catalan	Spanish
Dutch	***P = 0.18***						
Polish	*P = 1*	*P = 0.84*					
French	*P < 0.001*	*P = 0.02*	*P = 0.18*				
Italian	***P < 0.001***	*P = 0.006*	*P = 0.02*	*P = 0.68*[c]			
Catalan	*P < 0.001*	*P = 0.01*	*P = 0.007*	*P = 0.51*	*P = 0.04*[c]		
Spanish	***P = 0.006***	*P = 0.21*	*P = 0.04*	*P = 0.97*[c]	*P = 1*	***P = 0.68***[c]	
Japanese	***P < 0.001***	***P < 0.001***	*P < 0.001*	*P < 0.001*	*P < 0.001*	*P < 0.001*	*P < 0.001*

[a] Pairs for which behavioral data is available are shown in boldface.

[b] Statistical significance is shown for Mann–Whitney tests of the group factor over 40 subjects.

[c] For these pairs of languages, the control group was above the experimental group (See Section 4.2.4).
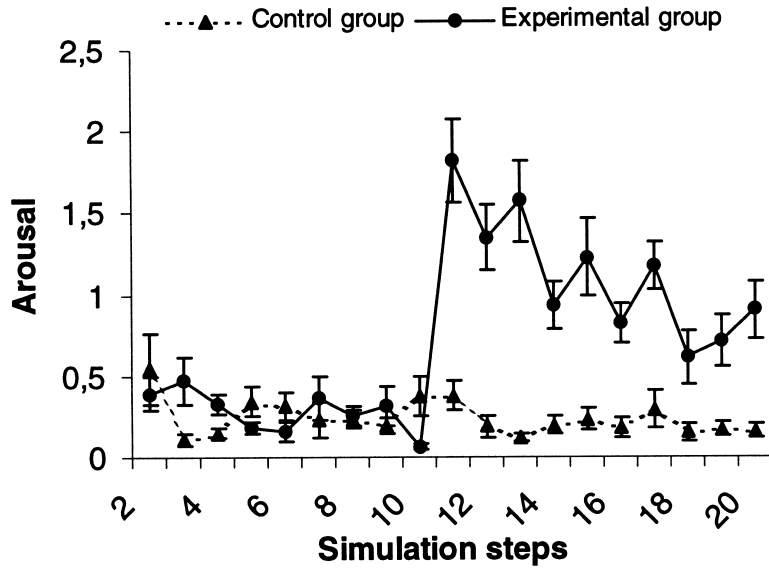
Fig. 5. Simulated arousal pattern for English/Japanese discrimination. Twenty subjects per group. Error bars represent ± 1 standard error.
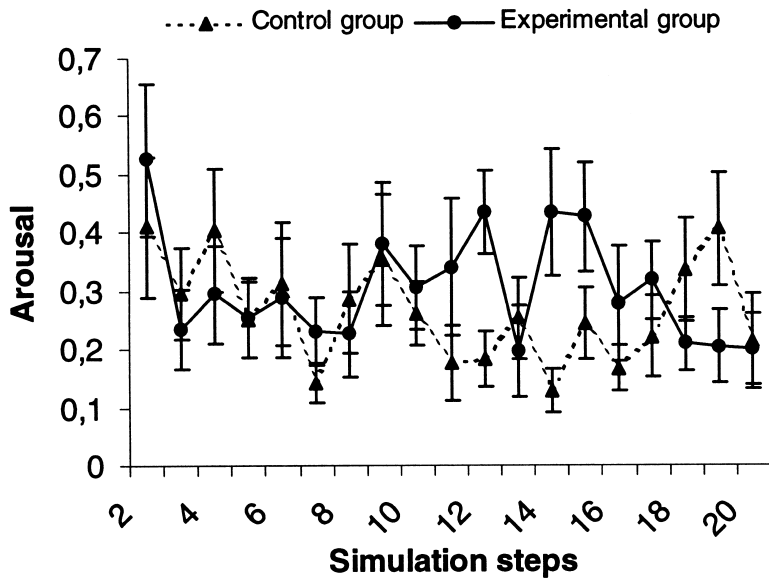

Fig. 6. Simulated arousal pattern for English/Spanish discrimination. Twenty subjects per group. Error bars represent ± 1 standard error.
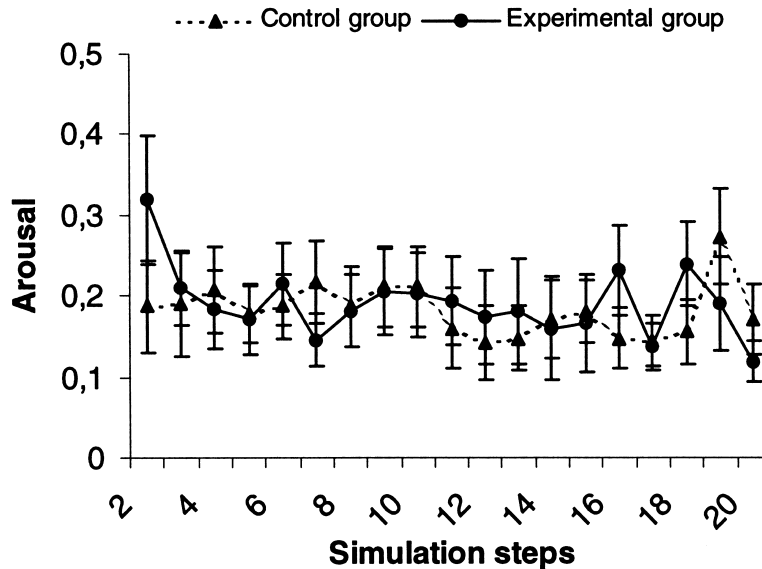
Fig. 7. Simulated arousal pattern for Spanish/Italian discrimination. Twenty subjects per group. Error bars represent ± 1 standard error.

contradiction with these predictions, it seems to us that they are not completely compatible with the otherwise high coherence of our data. Only future research, consisting both of measurements on more samples of these languages, and of the corresponding discrimination experiments, will tell us whether these predictions reflect an idiosyncrasy of our present corpus or more profound links between the concerned languages.

4.2.5. Groups of languages

In Nazzi, Bertoncini and Mehler (1998) discrimination between groups of languages has also been tested (Table 3). We have simulated this experiment as well, following the design of the experiment as closely as possible. As in the real experiment, the number of speakers is reduced to two per language. Subjects in the experimental group switch from English + Dutch to Spanish + Italian, whereas subjects in the control group switch either from Spanish + Dutch to Italian + English, or from Spanish + English to Italian + Dutch, with the order of the groups of languages counterbalanced across subjects. Within a phase, sentences are drawn at random from the assigned set, irrespective of their language. As in the previous simulations, there are half as many sentences as in the real experiment, that is ten sentences uttered by two speakers per language.

Notice that in this experiment there is no control group *stricto sensu*, that is a group having the same habituation phase as the experimental group. Indeed, subjects in the control group are presented a different combination of languages as compared to subjects in the experimental group. Thus, there is no guarantee that the prototypes

P_{10} will be the same for both groups at the end of the habituation. Assessing discrimination through comparison of average arousal in the test phase only is therefore not appropriate. Here, we use as dependent variable the difference in average arousal between the nine sentences following the switch and the nine sentences preceding it

$$\frac{1}{9}\left(\sum_{n=11}^{19} A_n - \sum_{n=2}^{10} A_n\right)$$

(recall that A_1 is not defined).

Thirty-two subjects are simulated, the same number as in the experiment. There is a main effect of group ($P = 0.01$), showing that arousal significantly increases more when switching from one rhythm class to the other, than when switching between incoherent pairs of languages.

4.3. Discussion

With the exception of the French/Russian pair, which was not available, the overall pattern of success and failure to discriminate languages shown in Table 3 has been entirely simulated and predicted, on the basis of a simple model. This model assumes that subjects can compute the vowel/consonant temporal ratio %V and that their categorization of sentences and languages is based on %V. In the one case where the direct comparison of categorization results for individual sentences was possible (English/Japanese in adults), subjects' scores were found to be highly consistent with predictions based on %V, comforting the psychological plausibility of this model.

The generality of the agreement between the behavioral data and the simulations is still limited in several respects:

1. By the set of languages used in the behavioral experiments on the one hand, and in the simulations on the other hand. Certainly, the agreement only holds for the pairs of languages studied both in the experiments and in the simulations. Indeed, future behavioral results could well disconfirm the predictions of the simulation. It is for this reason that we have provided predictions for all pairs of languages present in our corpus, not only those for which a behavioral result is already available. These predictions await further language discrimination studies, be they in adults or in newborns.
2. By the potentially infinite number of variables that can in principle be derived from the durations of vocalic and consonantal intervals. In the present paper we have computed three variables, and shown that one of them leads to the right predictions. If the pattern of behavioral results were to change or to be extended, would it not always be possible to derive a variable that could fit the new pattern?

In this respect, it is reassuring that the variable used in the simulation is the most straightforward to compute from the durations, %V, and not some sophisticated ad-hoc variable. ΔC and ΔV also follow quite directly. More importantly, all three variables are interpretable from the phonological point of view, in the sense that they are directly linked to the phonological properties supposedly responsible for

speech rhythm (see Section 3.5). But could ΔC and ΔV have predicted the same results as $\%V$? As we have explained, we chose $\%V$ on the basis of (1) consistency with the rhythm classes and their phonological properties, (2) its smaller variance than that of ΔC. From Fig. 1 we can guess that ΔC would have predicted the same pattern of results, but simulations might have been less sensitive. As regards ΔV, Fig. 2 suggests that this variable makes different predictions. Most notably, it suggests that it might be possible to discriminate Polish from English and Dutch. We checked this by running again both the logistic regression and the arousal pattern simulation on the English/Polish and Dutch/Polish pairs using the variable ΔV. The logistic regression gave 85 and 87.5% classification scores respectively, and the arousal pattern predicted both discriminations at $P < 0.001$.

Unfortunately these pairs of languages have never been experimentally tested, so it remains an open question whether ΔV can contribute to modeling the subjects' behavior, that is whether the most appropriate model should be based on $\%V$ alone, ΔV alone, or both. In the latter case, the respective weighting of the variables would be an additional parameter to adjust.

5. General discussion

Phonetic science has attempted to capture the intuitive notion that spoken languages have characteristic underlying rhythmic patterns. Languages have accordingly been classified on the basis of their rhythm type. However, although many characteristics of the speech signal have been measured, reliable acoustic characteristics of language classes have not been identified. Measurements estimating the periodicity of either inter-stress intervals or syllables have not helped capturing these intuitive categories, and attempts to classify languages on the basis of acoustic measures have mostly been abandoned. In this paper, however, we have presented measurements of the speech signal that appear to support the idea that the standard rhythm classes are meaningful categories, that not only appeal to intuitions about rhythm, but also reflect actual properties of the speech signal in different languages. Moreover, our measurements are able to account for infant discrimination behaviors, and thus provide a better understanding as to how a coarse segmentation of speech could lead infants to classify languages as they do.

What can we conclude from the reported data? Taken alone, the fact that the proportion of vocalic intervals ($\%V$) and the variability of consonantal intervals (ΔC) in eight languages are congruent with the notion of rhythm classes does not demonstrate that all spoken languages can be classified into just a few categories. At this point, we are agnostic about whether all languages can be sorted into a few stable and definite rhythmic classes. We only studied eight languages, and they were selected from those used by linguists to postulate the three standard classes. Hence, more languages have to be studied. It is entirely conceivable that the groupings already established may dissolve when more languages are added. Indeed, by adding other languages the spaces between the three categories may become occupied by intermediary languages yielding a much more homogeneous distribution. This

continuous distribution would be a challenge to the notion that languages cluster into classes and would show that it is the scarcity of data points that is suggestive of clusters rather than the way languages actually pattern. Alternatively, adding more languages to this study may uncover additional classes to the three we illustrate in this study.

This possibility is consistent with typological work by Levelt and van de Vijver (1998), who have proposed five classes of increasing syllable markedness (= syllable complexity). Three of these classes appear to correspond to the standard rhythm classes (Marked I, III and IV in their typology). One class (Marked II) is postulated for languages whose syllable complexity is intermediate between syllable-timed and mora-timed languages. One more class (Unmarked) is postulated beyond Japanese (this class consists of strictly CV languages). Since languages of the Unmarked and Marked II types are not part of our corpus, we cannot assess the relevance of these two additional classes, but in Fig. 1, for instance, there seems to be space for a distinct class between Catalan and Japanese, and of course there is also space for another class beyond Japanese. Using another rationale, Auer (1993) has also proposed five rhythm classes, which seem to overlap only partially with those mentioned above. Given all these considerations, we believe that the notion of three distinct and exclusive rhythm classes is the best description of the current evidence, but cannot be accepted until much more data becomes available.

Additional reasons encourage us to continue this line of research. Firstly, it seems that well-organized motor sequences require precise and predictable timing (Allen, 1975; Lashley, 1951). Language is a very special motor behavior but there is every reason to expect it to have a rhythmical organization comparable to that found in other motor skills such as walking or typing. Why should a language like English have such a very different periodic organization from, say, Japanese? Could it be that language has to conform to a basic rhythm that can be modulated by the adjustment of a few settings? It is too early to answer these questions. But at least there are reasons to think that the temporal organization of language, like that of every other activity, should not be arbitrary. And as for virtually every linguistic property showing variation across languages, we may expect rhythmic organization to take a finite number of values.

If putative rhythmic classes existed they would furthermore comfort theorists who postulate that phonological bootstrapping is an essential ingredient of language acquisition (Christophe & Dupoux, 1996; Gleitman & Wanner, 1982; Mehler et al., 1996; Morgan, 1986; Pinker, 1984). Indeed, if all languages could be sorted into a few rhythm classes, the likelihood that the properties underlying the classes might be cues that allow for the setting of grammatical parameters would be increased. Correlations between rhythm type and some syntactic parameters have been proposed in the past. For instance, syllable-timed languages have been associated with Complement/Head word order and with prefixing, while stress-timed languages have been associated with Head/Complement and suffixing (Donegan & Stampe, 1983). Even though such correlations would greatly help language acquisition, they do not hold beyond the languages studied by the authors (see Auer, 1993 for a more thorough critique, and Nespor, Guasti, & Christophe, 1996 for more

plausible cues to word order). We propose, instead, that rhythm type could help acquire some phonological properties that are less evident in speech.[9] A number of properties seem to be more or less connected with rhythm: vowel reduction, quantity contrasts, gemination, the presence of tones, vowel harmony, the role of word accent and of course syllable structure (Dauer, 1987; Donegan & Stampe, 1983; see Auer, 1993 for a survey). Given the current state of knowledge, we believe that only syllable structure is reliably related to rhythm.

The idea that rhythm might cue the acquisition of some other phonological property was already present in earlier formulations claiming that speakers of different languages use different segmentation units, and that rhythm is the cue that allows the infant to select the correct unit (Cutler et al., 1986; Mehler et al., 1996; Otake et al., 1993). The notion that languages have radically different units should give way, we think, to the more general notion that languages have different principles governing the structure that their syllables may take. We hypothesize that an early determination of rhythm type may allow the child to set some of these principles.[10] This hypothesis can be more explicitly formulated using the formalism of the current linguistic theories.

Within the Principles & Parameters theory (Chomsky, 1981), syllable structure is described by the values taken by binary parameters such as Complex Nucleus, Obligatory Onset, Complex Onset, Coda, Complex Coda (Blevins, 1995). The available evidence suggests that (1) mora-timed languages have (−Complex Onset) and (−Complex Coda), (2) syllable-timed languages have (+Complex Onset) and (+Coda), (3) stress-timed languages have (+Coda), (+Complex Onset) and (+ Complex Coda). Rhythm could thus trigger the setting of two or three parameters at once. In addition to this deterministic triggering, rhythm may also impose constraints on the possible combinations of parameters.

Within Optimality Theory (Prince & Smolensky, 1993), syllable structure is described by the ordering of structural constraints like Onset, *Coda[11], *Complex-Onset, *Complex-Coda, and faithfulness constraints like Fill and Parse. Syllable complexity (markedness), is reflected in the ranking of the faithfulness constraints with respect to the structural constraints (Levelt & van de Vijver, 1998). Each level of the faithfulness constraints corresponds to a class of languages sharing the same markedness of syllable structure, hence the five classes of languages mentioned above. Regardless of whether there are actually three or five such classes, it thus appears that knowing the type of rhythm could enable the infant to establish the ranking of the faithfulness constraints in the language she is learning.

Although the acquisition scenarios described above remain speculative, they provide a set of hypotheses that can be tested by studying the acquisition of syllables

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[9] Such a process would probably not be called phonological bootstrapping by those who coined the term, who meant bootstrapping of syntax through phonology.

[10] It should be noted that syllable structure is not necessarily transparent in the surface: before the infant can actually parse speech into syllables, syllable boundaries are evident only at prosodic phrase boundaries, which gives only partial and dissociated evidence as to which onsets, nuclei and codas are allowed.

[11] *Stands for No.

by infants in greater detail. We thus hope that the present work may contribute to clarifying the mechanisms through which infants acquire the phonology of their native language.

Acknowledgements

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