MENTAL LEXICON:
"SOME WORDS TO TALK ABOUT WORDS"

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Chapter 10

DISTRIBUTIONAL PROPERTIES OF LANGUAGE AND SUB-SYLLABIC PROCESSING UNITS

Ronald Peereman,* Nicolas Dubois Dunilac, Pierre Perruchet
Université de Bourgogne, Dijon, France
and Alain Content
Université libre de Bruxelles, Brussels, Belgium

ABSTRACT

During the past few years, several studies have drawn attention to the role of distributional characteristics in the segmentation of speech into word units. In the present chapter, we examine the role of distributional constraints in the acquisition of sub-syllabic language processing units. In particular, we suggest that specific processing units such as the rime might emerge from the distributional properties of sequences of vowels and consonants. We then summarize recent work showing that speakers are indeed sensitive to statistical distributions between vocalic and consonantal segments within the syllable. Finally, a simulation study using the Parser model (Perruchet & Vinter, 1998) indicates how probabilistic constraints can influence the acquisition of representational units. We conclude that what can be viewed as processing units probably represents only the tip of the iceberg of broader knowledge about statistical properties of language and that the acquisition of such representational units is, at least partially, shaped by general learning processes.

INTRODUCTION

In most contemporary models, language recognition and use are supposed to hinge on a set of intermediate representational processing units of various sizes. For example, it has been claimed that syllables constitute processing units in auditory word recognition, at least for

* Corresponding author: Ronald Peereman, L.E.A.D. – C.N.R.S Pole AAFE, Esplanade Erasme, 21000 Dijon, France, Email: peereman@u-bourgogne.fr

syllable-timed languages (e.g., Mehler, Dommergues, Frauenfelder, & Segui, 1981; Mehler, Dupoux, & Segui, 1990, for French; also Pitt, Smith, & Klein, 1998, for English), as well as in language production (Levelt & Wheeldon, 1994). Hypotheses about sub-word units have particularly flourished in the study of visual word recognition where graphemes (Rey, Ziegler, & Jacobs, 2000), rimes (Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995), and syllable units (Ferrand, Segui, & Grainger, 1996) have all been proposed as underlying reading processes. Two key characteristics of these proposals are that the processing units envisaged often correspond to units of linguistic description, and that their acquisition is generally not considered. In this chapter, we focus on the role of distributional properties of languages as one critical determinant in the specification of language processing units. We propose that what can be viewed as processing units probably represents only the tip of the iceberg of broader knowledge about statistical properties of language and that the emergence of such representations is, at least partially, shaped by general learning processes.

During the last decade, the role of distributional properties of language has mainly addressed the problem of word segmentation in the speech stream. Several studies (e.g., Jusczyk & Aslin, 1995; Mattys & Jusczyk, 2001; Myers, Jusczyk, Kemler Nelson, Charles-Luce, Woodward, & Hirsh-Pasek, 1996) suggest that young children are able to segment the continuous speech flow into individual words by using prosodic and segmental cues. Learning of the statistical regularities of the language is also suggested by the observation that 9-month-old children listen longer to words that include frequent phonetic sequences than to legal but rare phonetic sequences (Jusczyk, Luce, & Charles-Luce, 1994). Finally, Saffran and colleagues (Saffran, Newport, & Aslin, 1996) have showed that adults exposed to an artificial language composed of continuous tri-syllabic sequences without signification were able to learn the language by using the transitional probabilities between the syllables defining the word boundaries. Hence, although word units correspond to conscious and explicit units of analysis, their individualization requires segmentation of the speech stream. What the current studies suggest is that segmentation into word units is driven by basic learning mechanisms taking advantage of the statistical properties of the language.

Statistical regularities of the language are however not restricted to the cues associated to word and syllable boundaries. Within the syllable, certain phonemic sequences are more likely to occur than others (Coleman & Pierrehumbert, 1997; Kessler & Treiman, 1997). For example, in English, the consonants /h/ or /j/ only occur at the beginning of Consonant-Vowel-Consonant (CVC) syllables whereas the reverse is true for the /ŋ/ phoneme (Kessler & Treiman, 1997). In addition to these positional regularities, constraints also exist in the co-occurrence of phonemes within syllables so that sequences such as /ɥr/ or /ol/ are more frequent than /ɥp/ or /pl/ (Kessler & Treiman, 1997). Given such regularities, it can be expected that the mechanisms at work in learning to segment speech into words also lead to speakers' sensitivity to groups of sounds of various grain sizes at the sub-word level.

In what follows, we focus on the case of distributional constraints occurring between vocalic and consonantal segments. We start by discussing some empirical findings suggesting that the rime (i.e., the vowel and the following consonants) of monosyllabic words has a special status in processing written language. We show that the standard account of why rimes behave so specifically in reading does not explain recent data collected in French (Peereman & Content, 1997; Peereman & Dubois-Dunilac, 1999; Dubois-Dunilac, Peereman, & Content, 2003). We therefore turn to an alternative account in terms of distributional statistics characterizing sequences of vowels and consonants that correspond to rime units. We then summarize some recent work showing directly that speakers are sensitive to the statistical distributions of vowels and consonants within the syllable. Finally, a simulation study using the Parser model (Perruchet & Vinter, 1998) is reported, which indicates how probabilistic constraints of the input can influence the acquisition of representational units.

THE CASE OF THE RIME

The rime unit constitutes an interesting case to consider for at least two reasons. First, relative to other units such as syllables for which controversies exist (e. g., Content, Meunier, Kearns, & Frauenfelder, 2001 for spoken language; Brand, Rey, & Peereman, in press; Schiller, 1998 for written language), its importance in processing English orthography is well documented. Second, descriptive statistics on rimes and their constituents have been recently provided for both English and French (De Cara & Goswami, 2002; Kessler & Treiman, 1997; Peereman & Content, 1997, 1998).

Several studies indicate that, for English, the orthographic counterpart of the rime unit (i.e., the *body* unit that corresponds to the final VC letter group of monosyllabic words) has a special status in visual word recognition. It has been repeatedly found that it is essentially at the level of the body-rime correspondence that the degree of systematicity of the mapping between orthography and phonology influences reading performance in children (Backman, Bruck, Hebert, & Seidenberg, 1984; Laxon, Masterson, & Coltheart, 1991; Laxon, Masterson, & Moran, 1994) and adults (Glushko, 1979; Jared, 2002, Treiman et al., 1995). Letter strings are named more slowly and less accurately when alternative phonological codes can be assigned to the body unit (e. g., *-AVE* in the words *HAVE* or *WAVE*). Furthermore, sensitivity to rhyme in preliterate children has been claimed to constitute a good predictor of later success in reading acquisition (e.g., Bryant, MacLean, Bradley, & Crossland, 1990; Kirtley, Bryant, MacLean, & Bradley, 1989). The central place of body-rime associations in reading words seems to result, at least partially, from statistical characteristics of English orthography. Several analyses of the relations between orthography and phonology carried out on lexical corpora indicate that the pronunciations of English vowels are often inconsistent (Stanback, 1992; Treiman et al., 1995). In particular, the same orthographical vowels can often be associated with different pronunciations in different words. Treiman et al. (1995) estimated that nearly 38% of English CVC words include vowels that receive alternative pronunciations in different words. Interestingly, vowel inconsistency drastically reduces when the coda (i.e., the consonant(s) following the vowel in the syllable) is used as contextual information in deriving the vowel pronunciation. In the Treiman et al. counts, vowel inconsistency dropped to 20% when computed as a function of the coda. It is thus likely that the particular status of the body-rime unit follows from the fact that readers draw on of the contextual information provided by the coda when deriving the phonological code of vowels. To account for such observations, several models assume that readers convert print to sound using associations between body and rime units (e.g., Norris, 1994; Patterson & Morton, 1985; Taft, 1991; Zorzi, Houghton, & Butterworth, 1998).

Although the print-to-sound characteristics of the rime seem to offer interesting perspectives to account for the empirical findings for English readers, other observations indicate that the particular status of the rime has additional foundations. Indeed, studies (e. g., Kirtley et al., 1989; Stanovich, Cunningham, & Cramer, 1984) show that kindergarten children perform better when asked to detect the initial phoneme than the final phoneme of words, therefore suggesting that words are more easily segmented into onset and rime. When asked to split syllables, children prefer to segment into onset-rime than after the vowel (Fowler, Treiman, & Gross, 1993; Treiman, 1983). A preference for onset-rime segmentation is also observed when training beginning readers to read words. For example, Wise, Olson, and Treiman (1990) found that children learned to read words faster when trained with onset-rime segmentations than when trained with words segmented after the vowel.

A different way to evaluate the role of print-to-sound consistency in reader's reliance on body-rime units is to assess whether similar observations can be obtained when such orthographic peculiarities do not exist. French is interesting in this respect since, contrary to English orthography, the body-rime association does not seem to manifest a particular advantage with regard to the consistency of print-to-sound associations. Running statistical counts similar to those of Treiman et al. (1995) but on a French word corpus, Peereman and Content (1997; see also Peereman & Content, 1998) observed that print-to-sound consistency for vowels and consonants did not significantly improve when the contextual information brought by the whole body-rime unit was taken into account. For example, mean consistency of vowel pronunciation was 92% when the coda was not considered. Including the coda information in the computation did not cause a reliable increase in vowel consistency (95 %), contrary to English counts (Peereman & Content, 1998; Treiman et al., 1995). Does this imply that French readers would not be sensitive to body-rime characteristics when converting print to sound as required by a naming task? This is not the case. Indeed, in several studies (Dubois-Dunilac, Peereman, & Content, 2003; Peereman & Content, 1997; Peereman & Dubois-Dunilac, 1999) it was found that the frequency of body-rime associations in orthographically similar words was a good predictor of naming performance, whereas frequency of other units (e. g. the initial *CV* unit that includes the initial Consonant(s) and the following Vowel) did not contribute to performance. In sum, observations suggest that skilled readers rely on body-rime relations even when the characteristics of the print-to-sound mapping do not particularly favor reliance on body-rime associations. It thus seems that other reasons should be considered in order to account for the empirical data.

DISTRIBUTIONAL STATISTICS AT THE SUB-SYLLABIC LEVEL

Natural languages entail subtle regularities at different levels of analyses. Although most of the attention has initially concerned print-to-sound mapping (e.g., Seidenberg & McClelland, 1989), several studies have demonstrated that people are sensitive to other distributional aspects of language such as phonotactic patterns (e.g., McQueen, 1998; Vitevich, Luce, Charles-Luce, & Kemmerer, 1997). Interestingly, both Peereman and Content (1997) and Kessler and Treiman (1997) observed that, on average, rime units differ from other multi-phoneme units in term of the cohesiveness of their constituents. The analyses carried out by Peereman and Content on Consonant-Vowel-Consonant (CVC) French words aimed to examine whether there were more constraints on the groupings of vowels and codas (i.e., the constituents of the rime) than of initial consonants (onset) and vowels (CV units). Relative to the number of potential groupings computed as the mere product of the number of different vowels and different codas (for rime units) or different onsets and different vowels (for CV units), it appeared that that the proportion of existing rimes was smaller that the proportion of existing CV units (18.6% vs. 25.2 %). Hence, permissible Vowel-Coda sequences seem more constrained than Onset-Vowel sequences.

Similar conclusions for English were reached by Kessler and Treiman (1997) using an approach that has the advantage of taking articulatory feasibility into account. Indeed, instead of estimating the percentages of the units realized in the language relative to all combinations of segments, Kessler and Treiman estimated whether rime and CV units that *really occur* in CVC English words contrasted in terms of probabilistic constraints between their constituents. Computations were based on contingency tables that allow to assess how well each constituent (vowel or consonant) predicts the identity of the other (consonant or vowel). More precisely, the authors estimated the strength of the relationship between the two phonemes constituting rime or CV units, taking into account bi-directional transitional probabilities (probability of the second phoneme given the first, and vice-versa) and the frequency of individual phonemes. The resulting statistic, r phi, is equivalent to a Pearson r in the case of dichotomic data (see Perruchet and Peereman, 2003, for further discussion). The authors observed that contingency, as indexed by r phi, was higher between vowels and codas than between onsets and vowels. In other words, there are more constraints in combining certain vowels with certain codas than in combining certain onsets with certain vowels. Therefore, as claimed by Treiman, Kessler, Knewasser, Tincoff and Bowman (2000), "English speakers" tendency to treat rimes as units may reflect their experience with the correlations between vowels and final consonants that exist in their language". This conclusion is interesting because it also implies that empirical evidence for particular processing units could reflect statistical learning rather than the acquisition of representational units per se.

Analyses similar to Kessler and Treiman (1997) were performed on the French language. The r phi coefficient was computed for all CV sequences included at the beginning of words (number of words = 21,710), and for all VCs at the end of words (n = 14,963). The lexical corpus corresponded to words appearing in the Brulex database (Content, Mousty, & Radeau, 1990). The results are provided in Table 1. Note that the r phi values vary between –1 in case of inverse interdependencies and 1 when contingency is maximal. As can be seen, there were more different CV than VC units. For each sequence, a Chi-square test was performed to examine whether the two phonemes occurred together more frequently than predicted by chance given the frequency of each individual phoneme in the corpus. Row 2 of Table 1 indicates the percentage of two-phoneme strings that occur significantly more often together than predicted (at $p < .01$). Although the percentage of cohesive sequences was similar for VC and CV sequences, a sharper difference was observed when association values were averaged. As indicated in the third row, VC sequences were on average more cohesive than CV sequences.

The observation that certain phonemes are more strongly associated with each other than predicted by chance does not guarantee that people pick up such distributional patterns. Several studies indicate, however, that an implicit knowledge of phonotactic structures develops as a function of language exposure. By 9 months, young children prefer to listen to syllables that obey phonotactic rules than to illegal syllables (Friederici & Wessels, 1993; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993) and they also exhibit a preference for high over low probability phonotactic sequences (Jusczyk et al., 1994). When asked to judge how much nonwords are wordlike (phonological goodness judgment), adults rate nonwords with high transitional probabilities between phonemes as more wordlike than nonwords with low transitional probabilities (e.g., Frisch, Large, & Pisoni, 2000; Vitevitch, Luce, Charles-Luce, & Kemmerer, 1997). Nevertheless, until recently, there have been few attempts to find out which specific probabilistic cues are indeed learned, and variables such as frequency, transitional probability, and contingency are generally confounded in the existing studies. Indeed, it is generally the case that the manipulation of transitional probabilities between phonemes entails correlated variations in the frequency of the whole biphone units (the two-phoneme strings), as well as in the frequency of individual phonemes. For example, analyses on the Brulex database mentioned above indicate correlations above .50 between transitional probabilities and biphone frequency. Moreover, a high correlation exists between the mean transitional probability between phonemes in a sequence and its similarity with real words; phonemic sequences with high transitional probabilities between phonemes having more phonologically similar words (lexical neighbors; Frauenfelder, Baayen, Hellwig, & Schreuder, 1993). Because similarity with real words has been shown to influence listeners in several tasks such as phoneme monitoring (Wurm & Samuel, 1997), word repetition (Dufour & Peereman, 2003; Luce & Pisoni, 1998) or phonotactic judgements (Bailey & Hahn, 2001), it is still unclear whether people are sensitive to phonemic transitions as such.

Table 1. Contingency Analyses of Initial CV and Final VC Sequences Occurring in French Words

	CV sequences	VC sequences
Number of different sequences	238	169
Percentage of cohesive sequences	22.7	21.9
Mean Phi value for cohesive sequences*	0.071	0.154

Note. * when $p < 01$

A few studies attempting to dissociate between some of the correlated measures have been recently described. While controlling for individual phoneme positional frequency, Treiman et al. (2000) showed that children and adults judged CVC nonsense syllables as more wordlike when they included a frequent rime unit, but lexical similarity with real words was not controlled. Bailey and Hahn (2001)'s study aimed to dissociate the role of lexical neighborhood and phonemic transitional probabilities in wordlikeness judgments. Interestingly, the results suggested that phonemic transitional probabilities accounted for performance over and above any influence of lexical neighborhood. Unfortunately, due to the correlation existing between the two variables, the role of transitional probability cannot be clearly dissociated from the role of the frequency of the whole biphone. More recently, some of us (Perruchet & Peereman, 2003) reported the results of a wordlikeness judgment task in which pairs of CVC nonsense French syllable were aurally presented to children and adults. For each pair, participants had to indicate which of two syllables sounded the most like French. To minimize memory requirements, each pair of syllables was presented twice, in succession. The experimental situation is illustrated in Figure 1. Syllables were contrasted on the phonemic contingency (r phi) between the vowel and the coda composing the rime. For example, in the syllable pair /nid/ - /nɑ̃s/, the vowel /i/ and the coda /d/ are more strongly associated than the vowel /ɑ̃/ and the coda /s/ (according to lexical corpus analyses). Correlational methods were used to estimate the contribution of various predictors to preference choices. It emerged that phonemic contingency as estimated by the r phi was the best predictor of performance. Children and adults judged CVC syllables as more wordlike when the constituents of the rime were highly contingent. Although frequency of the whole rime unit (e.g., the frequency of the rime /id/ in French words) also correlated with preference choices, its contribution was smaller and even vanished when phonemic contingency was introduced as a predictor in the same regression analysis. Also interesting was the observation that the simple transitional probability between the vowel and the coda (i. e. the probability of the coda given the vowel) was not a main determinant of preference choice. In sum, what appeared to guide participants in choosing the most wordlike syllable is the *two-way dependency* between the vowel and the coda as assessed by the r phi coefficient.

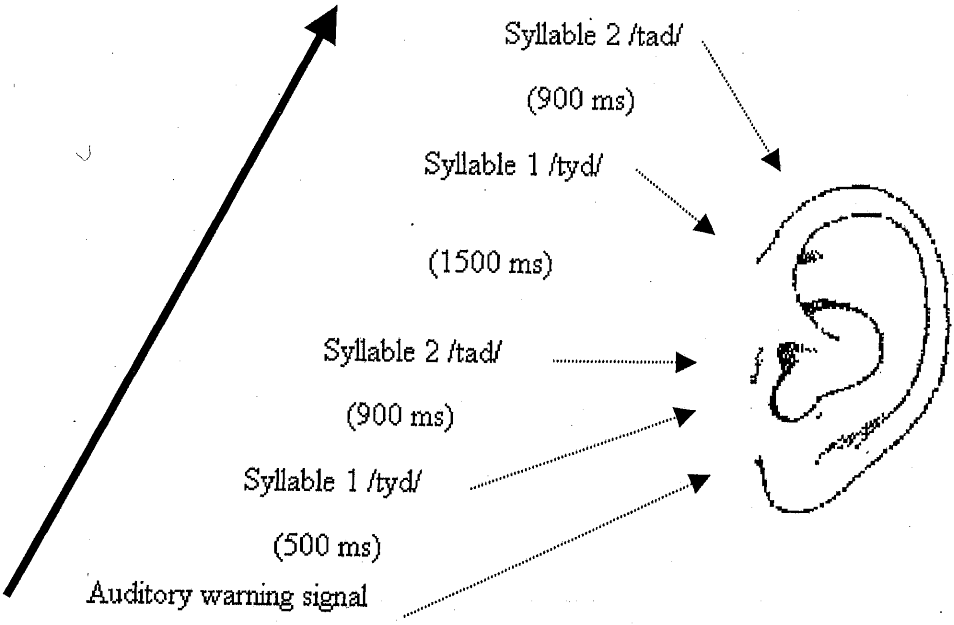

Figure 1. Experimental situation in the Perruchet and Peereman (2003) study

So far, a preliminary conclusion is that people are sensitive to the statistical interdependencies between phonemes. This observation is therefore in agreement with Treiman et al.'s (2000) hypothesis that the importance of rime units may follow from the fact that speakers implicitly learn the correlations existing between vowels and final consonants in their language. A question that arises is whether similar learning can be observed when phonemic contingency concerns other constituents than the rime. After all, if sensitivity to the correlations between vowel and coda is the result of general purpose learning mechanisms, then one might expect to find similar sensitivity in the case of other sub-syllabic dependencies. Accordingly, one reason why the rime units might have obscured learning of other sub-syllabic dependencies is that two-way dependencies are, on average, stronger for rimes than for other subsyllabic constituents (see also Treiman, Kessler, & Bick, 2003, for similar arguments for the role of rimes in reading). In what follows, we summarize the results of a recent study (Dubois-Dunilac et al., 2003) exploring this issue.

ONSET-VOWEL CONTINGENCY, SONORITY CONTRAST, AND AGE

The first purpose of the Dubois-Dunilac et al. (2003) study was to examine whether learning of phonemic dependencies could be extended to other syllabic constituents than the vowel and the coda. To this aim, Onset-Vowel contingency was manipulated. A second purpose, was to explore sensitivity to statistical dependencies as a function of age. It was expected that sensitivity should increase as a function of the speaker's experience with the language. Therefore, the study involved four age groups. Finally, the sonority contrast between the onset and the vowel was manipulated. Sonority is an ordinal scale devised by phonologists to express regularities in the phonemic composition of syllables. It is based on the contrast between the sonorant phonemes, which are characterized by a periodic vibration (e.g., vowels), and the phonemes characterized by a non-periodic noise, or obstruents (see, e.g., Selkirk, 1984). Other phonenes have intermediate sonority values. For example, unvoiced stop consonants such as /p/ or /k/ are assigned the lowest sonority level, followed by voiced plosives (/b/ or /g/). Liquids (/l/ or /r/) and nasals are intermediate, and glides are considered more sonorant, just below the vowels that represent the maximum point of the scale. The sonority level correlates with the degree of opening of the vocal tract, and this articulatory trait is sometimes used as a definition too. The sonority *contrast* refers to the difference in sonority between adjacent phonemes. As an example, the contrast is large for /pa/ since the sonority is minimal for /p/ and maximal for /a/. Conversely, the contrast is small for /la/ since the two segments have close sonority values. Several studies indicate that children and adults have fewer difficulties in segmenting CVC syllables when the sonority contrast is high between adjacent phonemes (e.g., Treiman, 1989; Yavas & Gogate, 1999). Inversely, word games by children show that consonants are more easily considered as forming a group with the vowel when the two phonemes contrast only slightly in sonority (e.g., Hindson & Byrne, 1997). Hence, the empirical manipulation of the sonority contrast represents an ideal situation to explore whether phonotactic sensitivity is actually dependent on the degree of association *between individual segments*. Indeed, learning phonemic dependencies should be a function of the ease with which the segments can be individualized. In other words, noticing probabilistic constraints in the ordering of phonemic sequences should be facilitated when phonemes can be easily isolated. It was therefore expected that sensitivity to onset-vowel dependencies would be larger when the sonority contrast was high.

Kindergarten, first-grade, and third-grade children took part in the experiment (n = 20, 30, 20, respectively). A group of 20 adults was also included. The task was similar to the one used by Perruchet and Peereman (2003) mentioned above. For each trial (n = 24), two CVC nonsense and legal syllables were presented twice, and participants had to decide which one of the two syllables was the most Frenchlike (e.g. /tyd/ - /tad/ where /t/ and /y/ are more contingent than /t/ and /a/). Syllables of each pair contrasted in terms of onset-vowel contingency, but were matched for the frequency of the whole CV unit as well as for the number of phonologically similar words (lexical neighborhood density). For half of the syllable pairs, the sonority contrast between the onset and vowel was small. For the other half, the sonority contrast was high. The results are shown in Figure 2. Performance corresponds to the preference percentages for the syllable including the most contingent onset-vowel sequence. Recall that because two syllables were presented, the chance level was .50. As can be seen, syllables including a contingent onset-vowel sequence were more often chosen by the participants, but only when the sonority contrast was high. When the sonority contrast was low, the responses were at chance level. For the high sonority contrast, it also clearly appears that sensitivity to onset-vowel contingency increases with age. The preference for contingent sequences which was not observed for kindergartners (chance level) progressively increased as a function of language exposure.

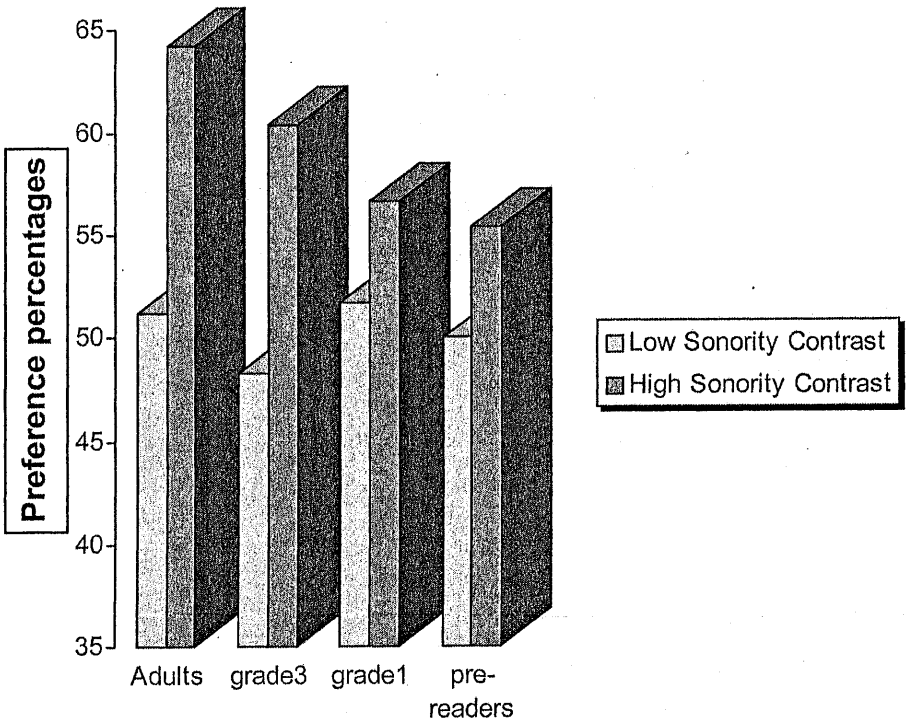

Figure 2. Preference percentages (chance level = 50) for the syllabe of the pair including the most contingent Onset-Vowel sequence, as a function of Age and Onset-Vowel Sonority Contrast (from Dubois-Dunilac et al., 2003)

The data indicate that phonotactic judgements are influenced by onset-vowel contingencies. Taking into account the controls that were carried out in stimulus selection, the effects are not reducible to effects of frequency of the whole CV diphones nor to effects of lexical neighborhood. The results thus suggest statistical learning of the correlation between adjacent phonemes. They also reveal that such learning is not restricted to VC sequences but that it probably occurs on any phonetic string. Also, as suggested by the effect of age, learning of the statistical co-variations between phonemes develops with language experience. Finally, the role of the sonority contrast in participants' preferences supports the hypothesis that learning co-variations between phonemes requires clear phonological segmentation.

At least two assumptions can be formulated to explain why kindergarteners were at chance level. A first possibility is that the children simply did not understand the task. A second possibility is that young children use more global cues to perform wordlikeness judgments. In particular, the young children could have tried to find phonological similarities between the target syllables and real words to evaluate wordlikeness. Adopting such a lexical similarity strategy in the experiment should produce no effect because syllables were matched for lexical neighborhood. This hypothesis gains some support from an additional experiment in which it was shown that phonological similarity with real words influenced wordlikeness judgments by kindergarteners.

Sensitivity to Statistical Regularities: What Learning Mechanisms?

In the preceding sections, we showed that people develop sensitivity to subtle co-variations between phonemes at the sub-syllabic level. An interesting question that arises is how statistical constraints existing in the language can influence the way language knowledge is organized in memory? As mentioned earlier, the distributional properties of the language seem to contribute to the acquisition of linguistic units. Such a hypothesis has been repeatedly put forward for the segmentation of word-equivalent units from exposure to the continuous speech stream (e.g., Brent & Cartwright, 1996). As far as sub-syllabic units are concerned, a similar proposal is that the rime units might have a special status due to the high cohesiveness of their constituents (Kessler & Treiman, 1997; Treiman et al., 2000).

Until now, sensitivity to the distributional aspects of language has generally been discussed within the framework of connectionist models that learn sequential probabilities. In these models, the elementary units are initially determined, and the weights of the connections between units optimised during a learning phase. An alternative view is to consider that the statistical properties of the language influence the acquisition of linguistic units. However, it is still unclear whether this alternative view allows to capture sensitivity to more subtle statistical variables than unit frequency, such as the transitional probabilities between the input elements. In what follows, we therefore explore the role of statistical constraints on unit acquisition using a computational model initially developed to simulate word segmentation in continuous speech (Parser; Perruchet & Vinter, 1998). Our main purpose in running the simulation studies was to investigate whether models such as Parser would represent an adequate alternative view to account for the sensitivity of speakers to the distributional properties of the language.

In recent years, learning of sequential regularities in speech has often been modeled with Simple Recurrent Networks (SRNs; e.g., Dell, Juliano, & Govindjee, 1993; Christiansen, Allen, & Seidenberg, 1998). As shown in Figure 3, the input units encoding the current element are connected to output units through an intermediate set of hidden units. Hidden units receive activation from both the input nodes and from the context nodes. Context units encode the state of activation of the hidden units when the preceding element was presented. The most common task used to train SRNs is to predict the next element of a sequence (Cleeremans & McClelland, 1991; Elman, 1990), for example the next phoneme of a speech sequence. The prediction of the next element as determined by the activation of the output units is a function of the activation of the input and context units. In this way, the prediction of the next element of a sequence depends on both the current and past elements presented to the network. Learning of the sequential probabilities between events is realized during the training phase by adjusting the connection weights between units so as to minimize the output error. Several simulation studies have demonstrated the power of SRNs in learning sequential properties of speech sequence. For example, the SRN trained by Christiansen et al. succeeded in predicting word boundaries in continuous speech by taking advantage of the higher phonemic dependencies existing within than across words. However, although SRNs represents an interesting and promising tool to discover statistical regularities between sequential events, it does not by itself formalize unit (e.g., word) acquisition. Furthermore, Perruchet and Peereman (2003) recently showed that SRNs learn statistical dependencies that do not exactly match what seem to be learned by people about phonemic contingencies. In particular, a shortcoming is that the SRN proved to extract standard feedforward transitional probabilities whereas language users seem more sensitive to bi-directional dependencies between phonemes.

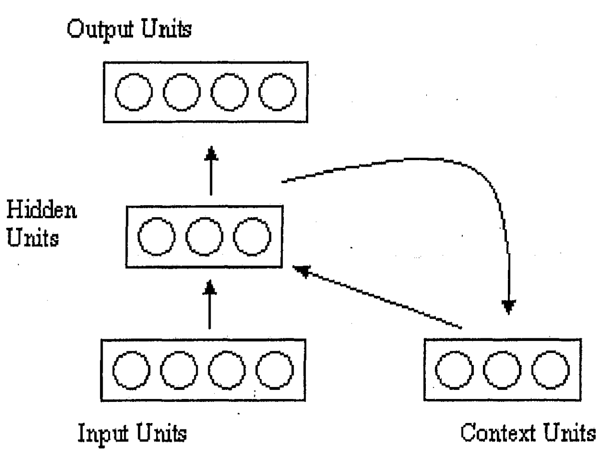

Figure 3. Illustration of a SRN

Unlike Simple Recurrent Networks, the Parser model propounded by Perruchet and Vinter (1998) does not include mechanisms designed to extract the distributional properties of the input. Hence, whereas the SRN can be conceived as learning phonotactics without acquiring linguistic units, in Parser, it is the way linguistic units are acquired that is a function of the probabilistic characteristics of the input. The model is illustrated in Figure 4. When a continuous stream of events (e.g., phonemes) is presented to the model, a sequence of events of random length is first chosen. This sequence can be conceived as corresponding to the elements entering attentional focus. The system then examines whether the sequence matches a unit already stored in memory. If not, a new representational unit is created which will be used thereafter to guide perception. If the unit already exists, its weight is updated. To survive, the stored units need to be reactivated during training. Indeed, due to forgetting mechanisms, units that are not reactivated disappear. At first glance, Parser is thus primarily sensitive to the frequency of successive events. The sequences frequently encountered are strengthened in memory and the others are forgotten. However a significant characteristic of the model is that forgetting is caused by both natural decay and interference. When a specific unit is recognized, all units that are similar (e.g., share phonemes or letters) have their weights decreased. The implementation of an interference mechanism allows the model to be sensitive to subtler measures of associations than the units' frequency.

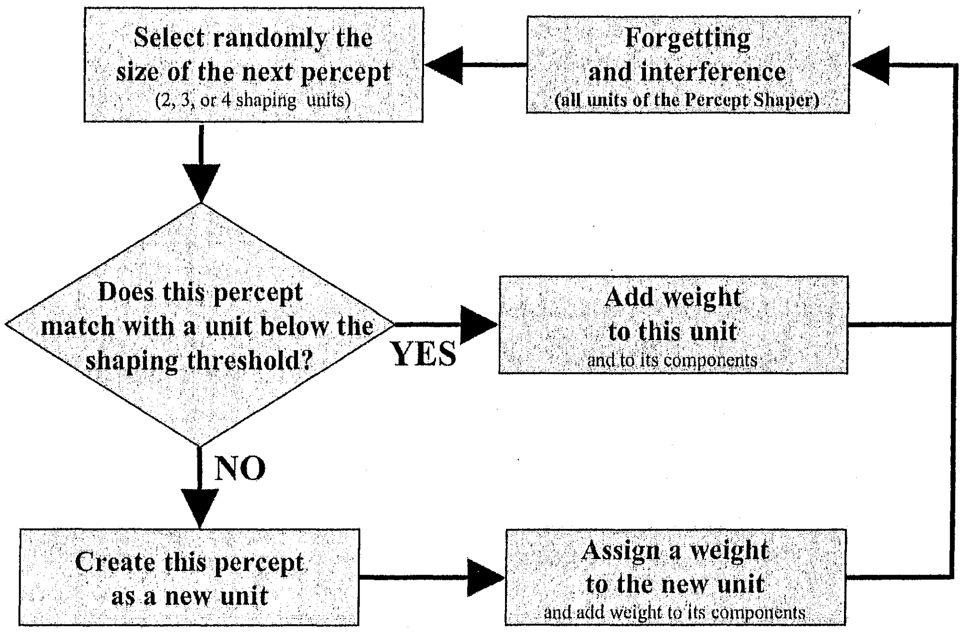

Figure 4. The Parser model (Perruchet & Vinter, 1998)

Simulations were performed using Parser to examine unit acquisition as a function of the contingency between successive events. Is such a model, which does not incorporate specific mechanisms to encode transitional statistics between events able to demonstrate sensitivity to the event contingencies observed in the empirical studies described above? The simulations used an artificial language in which "words" corresponded to letter pairs (e.g, AF, CH, EG, EI, BG, DI). Learning of the word-bigrams was assessed as a function of the contingency existing between the two letters of each pair. All word-bigrams were presented without space or separation, as in:

EIEGEGCHCHDFEGAFCHDJEGBHDHEGCKAGBGBGEIBIBIAFCHCHEGEGAFBI
DIAJDKAFDIEGBJCHDJBGDGBIEIDIEGEHBGEGEGDIEIDJAFDGEIBGEHEIBIDI

DGCIAFCFAFAFEFEGBKEIBJAFCHAFBJBGEGDFBJCHDKEIEGEIDIBFEIBGBG
DKEIDIAFAJBGEGBJBGDJCHAFBKBJBKBIEGCHAKEGBGCHBICKCHBKEGEI
BKDJBJAIDGCHBIDKAIBJAFBGBJDKAFEIBHEIDJDI......

The full list included 30 different word-bigrams repeated various times. The total length corresponded to 242 bigrams, and the list was presented 100 times to the model. One hundred distinct simulations (using different random word-bigram orders) were performed to simulate the results of 100 subjects. Simulation parameters were as in Perruchet and Vinter (1998) except that the interference value was increased relative to the original one. While interference was set to .005 in Perruchet and Vinter, we progressively increased its magnitude up to .20 in the present work. The simulation results reported below were obtained using an interference value of .10. We will summarize later the main variations in the data induced by the manipulation of the interference parameter.

Does Parser learn word-bigrams, and if it does, is there any advantage for contingent word-bigrams relative to non-contingent ones? To answer this question, we contrasted six particular word-bigrams. These bigrams differed on letter contingency as well as on the frequency of the whole bigram. Two of them (AF and CH) included letters that were highly contingent, but the bigrams occurred infrequently in the list (Condition "Contingent/Rare"). The reverse was true for two other bigrams (EG and EI) in which the letters were not contingent, but the bigrams occurred frequently in the list (Not Contingent/Frequent). Finally two additional bigrams (BG and DI) were not frequent and included non-contingent letters (Not Contingent/Rare). The remaining word-bigrams were fillers. They were included to obtain the desired level of contingency for the six target word-bigrams. The results presented below correspond to the number of simulations (among the 100 performed) in which the critical word-bigrams had been acquired as representational units. The data are depicted in Figure 5 as a function of the number of list repetitions (epochs). Note that neither the word-bigrams serving as fillers nor the inter-word bigrams corresponding to the last letter of one word-bigram and the first letter of the following word-bigram were acquired by Parser.

The two lines in the top of Figure 5 represent the increase in the learning of the two word-bigrams of the Contingent/Rare condition as a function of list repetition. These two bigrams were discovered faster than those of the Not-Contingent/Rare condition reported at the bottom of the Figure. It is therefore clear that unit acquisition in Parser is partially dependent on the contingency existing between the bigram constituents. Moreover, Parser seems more influenced by the contingency of the constituents than by the frequency of the whole unit. Indeed, as can be seen in the Figure, the two word-bigrams of the Not-Contingent/Frequent condition --represented by the two central lines-- were better than the Not-Contingent/Not Frequent condition, but were less frequently acquired than the two Contingent/Rare word-bigrams. Hence, in spite of being presented more frequently to Parser than the Contingent/Rare word-bigrams, they yielded less frequent formation of units in the model.

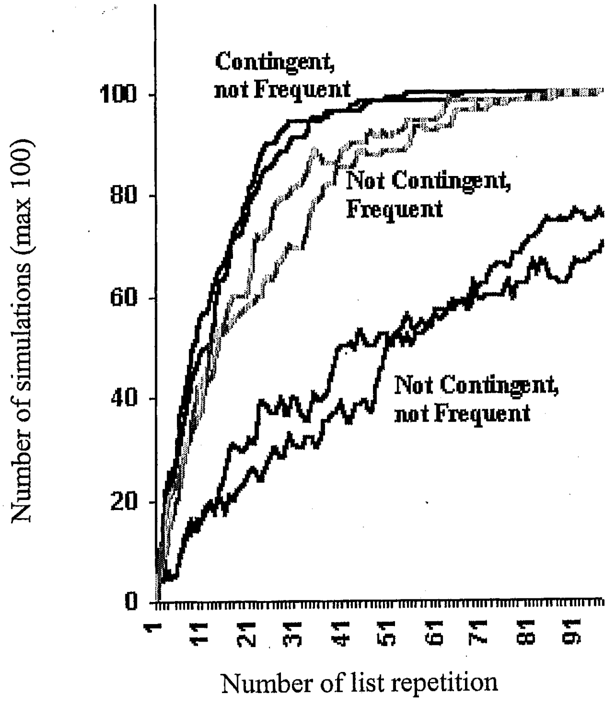

Figure 5. Number of simulations (max: 100) having acquired the critical lexical units (bigrams) as a function of contingency and frequency (there are two bigrams in each condition)

Whereas studies suggest that the discovery of words in the continuous speech stream can result from the distributional characteristics of the input, the present simulation demonstrates that sensitivity to the statistical regularities of the language can be the consequence of natural attentional processing. Beyond pure frequency effects, contingency between events was a main factor in the simulation results. This observation mimics the finding that phonotactic judgements are best explained by the r phi correlation between successive phonemes. In Parser, sensitivity to bi-directional dependencies between events does not result from the acquisition of knowledge directly encoding sequential probabilities, but it is the fruit of the interference that occurs between units during learning. When a particular unit (e.g., BG) is perceived, the units sharing a letter with that unit (e.g., BH, EG) are "inhibited" and the reduction in their weights brings them closer to forgetting. Units tend to be less repressed when they comprise contingent letters than when they include less contingent ones, because the probability of perceiving another unit sharing one letter with them is lower (e.g., if BH is perfectly contingent, this means that there is no unit such as BG in the corpus).

The role of interference between units in producing contingency effects in Parser is clearly shown by the manipulation of the interference parameter. In the simulations reported by Perruchet and Vinter (1998), Parser succeeded in learning word units using a very small interference value, but contingency between successive events and frequency of event sequences were correlated in the material. For example, inter-word bigrams (i.e., bigrams corresponding to the last letter of a word, and the first letter of the following word) were, in average, less frequent and less contingent than intra-word bigrams. Exploratory simulations using the material described above indicated that low interference values produced Frequency but not Contingency effects. By contrast, high interference values (e.g., .20) lead to Contingency but not to Frequency effects because interference between units precludes the acquisition of word units frequently encountered when they do not include contingent constituents (as it is the case for the EG and EI word-bigrams). It thus appear that the occurrence of Contingency and Frequency effects are dependent on the balance between forgetting due to natural decay and interference between units. Further simulation work currently in progress aims at examining whether such a balance can be adjusted as a function of the experimental context.

CONCLUSION

Various studies indicate that the statistical characteristics of language play a critical role in language acquisition and use. A full understanding of the mechanisms at work in extracting the distributional aspects of language requires to determine what characteristics are important, and how sensitivity to these characteristics develops. We believe that this enterprise is not only crucial for the study of general learning mechanisms, but also for any specific model of language processing including hypothetical representational constructs such as word or rime units. Although much of the previous work has addressed the role of statistical constraints in discovering words, we tried in the present chapter to explore whether language users are sensitive to phonemic contingencies defined at the sub-syllabic level. As we discussed, this interest was partially motivated by the hypothesis that sub-syllabic units such as the rime units would guide language processing, at least in written language.

Overall, the studies mentioned above suggest that listeners are able to pick up subtle phonemic co-variations in their language. Hence, when asked to perform a phonotactic judgment task, participants generally consider nonsense syllables that are made up of contingent phonemes as more typical or wordlike. We also showed that sensitivity to phonemic contingency develops with age and language exposure, and that it was not restricted to particular constitutents within the syllable. Moreover, as expected, sensitivity to phonemic contingency was observed to be dependent on the ease with which each segment can be individualized, as suggested by the role of the sonority contrast on the emergence of phonemic contingency effects. Finally, independently of specific hypotheses embodied in the Parser model, a particular interest of the simulations performed is that they clearly indicate that a learning system that is not specifically dedicated to the extraction of probabilistic properties of the input is still sensitive to statistical characteristics. Incidentally, the simulation results also suggest that the role of the frequency variable may have been overestimated in past studies. In particular, Parser performance was more dependent on the transitional characteristics of the input than on the frequency of particular event sequences. Thus, It seems clear that further research should be carried out to investigate in more detail the role of the transitional characteristics of the input in various cognitive processing.

If sensitivity to sequential regularities develops as a consequence of general learning mechanisms, then the representational structures that emerge from experience need not be similar or homologous for spoken and written language. Despite the primacy of spoken over written language, experiencing visual words might lead to particular groupings that do not exactly match spoken units. Thus, the distributional characteristics of the orthography might partially determine letter groupings, as suggested for example by Prinzmetal, Treiman and Rho's (1986) observation that syllabic effects for printed words did not strictly match phonological syllabification. The role of specific orthographic constraints is also sustained by findings recently described by Gombert and Peereman (2001) in a task in which kindergarteners learned to associate visual patterns with nonsense spoken CVC syllables. The visual patterns consisted either of three artificial symbols, or of three alphabetic characters. The learning trials were constructed so that the mapping between the visual strings and the CVC syllables was fully consistent (i.e., each visual symbol always mapped onto the same pronunciation). In the case of the alphabetic characters, the relation between each letter and its pronunciation was the one existing in French (e.g., the letter *A* for the /a/ vowel). In the case of artificial symbols, the letters were systematically replaced by non-alphabetical characters (e.g., a small square for the /a/ vowel). Three different learning conditions were used. In the "rime" condition, the training trials involved the combination of three different rimes with three different onsets so that extraction of the associations at the level of the onset and the rime should be faciliated. In the "initial CV" condition, the training trials involved the combination of three different intial CV with three different coda, so that the associations were to be learned at the level of the initial CV and coda. Finally, in a third condition, three different vowels were combined with three different onset-coda groupings so to require segmentations of the onset, vowel, and coda. After the learning phase, the children were tested for generalisation to new visual patterns. It appeared that associations involving large units (rime and initial CV) were better learned than associations requiring onset/vowel/coda segmentations. There was also an advantage of onset/rime associations over initial CV/coda associations when alphabetic characters were used, but not with *artificial* characters. A tentative interpretation of this finding is that the exploitation of the onset/rime segmentation by kindergartners results from their preliminary experience with the orthographic system. The greatest cohesion of vowels and coda could thus determine, or at least contribute, to the importance of the rime units in learning to read and in skilled reading. Because no such learning could have occurred for artificial visual patterns, no onset/rime segmentation advantage was observed.

An additional property that should characterize general learning mechanisms is that the learned dependencies between events should not necessarily be restricted to linguistic constituents such as syllables or rimes. In agreement with this hypothesis, recent observations indicate that dependencies can be learned between elements that do not correspond to particular units of linguistic analysis. For example, when asked to spell nonwords, children and adults make use of contextual information. In Pacton, Fayol and Perruchet, (2002), the spellings corresponding to the /o/ sound included in nonwords such as /povila/ or /borile/ were dependent on the identity of the surrounding orthographic context and were a function of the statistical regularities of the orthographic system. So, the French spelling AU was more likely to occur between the P and V consonants (e.g., /povila/), while /o/ was more frequently spelled O when occurring after B and before R (e. g., /borile/). Thus, processing units do not mirror linguistic units but result from the distributional properties of the language, a suggestion that was previously advocated by Seidenberg (1987; Seidenberg & McClelland, 1989). The fact that empirical observations have essentially focussed on certain units (e.g., the rime) would follow from a commitment to conceptually-driven linguistic analyses. Discovering new learned dependencies between phonemes or letters, and their influence on language processing, requires detailed and systematic lexical corpora analyses. Whether or not evidence of statistical learning should be considered within the framework of Parallel Distributed Processing models as suggested by Seidenberg and McClelland (1989) is however open to discussion. As shown by the Parser simulations (see also Perruchet & Peereman, 2003), a model acquiring localist representational units is also able to demonstrate sensitivity to subtle distributional constraints at various levels of analysis of the input. Whatever the theoretical framework adopted, both views suggest however that what have generally been considered as processing units only represent a fraction of a much more extensive knowledge of the statistical properties of language.

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