# Perceptual Constraints in Phonotactic Learning

Ansgar D. Endress
Harvard University, Cambridge MA

Jacques Mehler
International School for Advanced Studies, Trieste, Italy

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Ansgar D. Endress
Harvard University
William James Hall 984
33 Kirkland St
Cambridge MA 02139
Fax: +1 617-495-3886
ansgar.endress@m4x.org

**Abstract**

Structural regularities in language have often been attributed to symbolic or statistical general-purpose computations, while perceptual factors influencing such generalizations have received less interest. Here, we use phonotactic-like constraints as a case study to ask whether the structural properties of certain perceptual and memory mechanisms may facilitate acquiring certain grammatical-like regularities. Participants learned that the consonants $C_1$ and $C_2$ had to come from distinct sets in words of the form $C_1$VccV$C_2$ (where the critical consonants were in word-*edges*) but not in words of the form cV$C_1C_2$Vc (where the critical consonants were in word-middles). Control conditions ruled out attentional or psychophysical difficulties in word-middles. Participants did, however, learn such regularities in word-middles when natural consonant classes were used instead of arbitrary consonant sets. We conclude that positional generalizations may be learned preferentially using edge-based positional codes, but that participants can also use other mechanisms when other linguistic cues are given.

**Perceptual Constraints in Phonotactic Learning**

While speakers clearly learn to process and produce sentences they have never encountered before (e.g., Chomsky, 1957; von Humboldt, 1836), the underlying computations are much debated. Such computations have often been attributed to symbolic general-purpose mechanisms of the kind digital computers implement (e.g., Anderson, 1993; Marcus, 2001; Newell, 1980). In contrast to such computer-mind analogies, other authors proposed that the mind may be essentially a *statistical* general-purpose engine (e.g., Elman et al., 1996; McClelland, Rumelhart, & The PDP Research Group, 1986; Rumelhart, McClelland, & The PDP Research Group, 1986; Seidenberg, 1997). Such "one-size-fits-all" machinery, however, is not the only alternative to explain mental computations. Indeed, humans and other animals may use a collection of specialized computational tools to cope with the demands of their environment, and learning mechanisms in non-human animals are almost always heavily constrained and specialized (e.g., Fodor, 1983; Gallistel, 1990, 2000; Ramachandran, 1990). Such special purpose machinery may well be equally important to language, a conclusion that has been reached on computational grounds already when language was first studied as a mental faculty (e.g., Chomsky, 1957, 1965).

Here, we follow this naturalistic approach, and hypothesize that principles of perceptual and memory organization constrain the kinds of language-related regularities that learners can acquire. That is, we

do not merely claim that learning is hard when memory demands are high. Rather, we suggest that some regularities are learned through heavily constrained and specialized computational mechanisms derived from perceptual or memory organization, and that these mechanisms have structural properties that may make them particularly suitable for learning certain grammatical-like structures. As a case-study, we investigate the acquisition of "phonotactic" regularities constraining the sequential positions in which certain consonants can occur. We ask whether such regularities are learned through mechanisms similar to those used to track positions in sequence more generally. Such mechanisms use the sequence-edges as anchor points to identify the positions of elements inside a sequence. If such mechanisms can be deployed for constraining the permissible positions of consonants within words, we would have further evidence that some grammar-like regularities may be acquired using certain "perceptual or memory primitives" (POMPs). These primitives are specialized computational mechanisms devoted to one particular function in learning certain grammatical (and presumably other) structures, but deriving from principles of perceptual or memory organization.

## How general are mental computations?

Cognition evidently uses mental computations of some sort. Given how little we know about the mechanisms involved, many authors suggested to use computing machines that we understand as a

first-order model of mental computation – namely computers (e.g., Fodor, 1975; Newell, 1980; Pylyshyn, 1984). Historically, it was understood that the architecture of a computer had to be complemented with many computational special-purpose devices to efficiently deal with the plethora of sensory signals that surround us at any moment (e.g., Fodor, 1983; Gallistel, 1990). This is particularly true for language acquisition and use, where it was understood from the start that language acquisition can be explained only through special-purpose computational devices (e.g., Chomsky, 1957, 1965).

In recent years, however, computers seem have been raised to psychologically valid models of mental computation. For instance, Marcus (2001) proposed that "registers are central to human cognition [as to digital computers]" (p. 55), and discussed how neurons could implement registers (pp. 55-58). Registers are small amounts of computer memory that hold values that can be accessed by operations. If mental computation involves the manipulation of mental symbols, one would probably need some form of memory to hold the representations such that they can be manipulated (e.g., Gallistel, 2000; Pylyshyn, 1984). According to Marcus (2001), for example, this may work essentially like in a digital computer.

In an influential test of such views, Marcus, Vijayan, Rao, and Vishton (1999) showed that young infants can learn the structures AAB, ABA and ABB. The infants were familiarized with "sentences" like *le-di-di, wi-we-we,* and recognized the underlying structure during

the test phase, when it was carried by *new* syllables. Marcus et al. (1999) concluded that "infants [extracted] abstract algebra-like rules that represent relationships between placeholders (variables), such as 'the first item X is the same as the third item Y'" (Marcus et al., 1999, p. 79), which is essentially how a computer would process such structures.

Computers, however, are not the only generic architecture that has been proposed to account for many aspects of mental computation. Another example are statistical computations. One prominent form of statistical learning has been proposed to be deployed for, among other purposes, learning words from fluent speech (e.g., Saffran, Aslin, & Newport, 1996; Aslin, Saffran, & Newport, 1998), melodies from tone sequences (Saffran, Johnson, Aslin, & Newport, 1999), configurations from visual scenes (Fiser & Aslin, 2002), and syntactic dependencies (e.g., Saffran, 2001; Thompson & Newport, 2007); while these authors have acknowledged that many other cues contribute to learning in these domains, it seems nevertheless that a single, generic statistical learning mechanism may be instrumental for a wide array of learning situation.

However, it is well known that even the most typical examples of statistical learning – classical and operant conditioning – are not readily described by "one-size-fits-all" mechanisms, but rather are heavily constrained and specialized. For instance, rats easily learn to

associate tastes with visceral sickness, and external events (such as lights) with pain; the reverse associations are extremely hard to obtain (Garcia, Hankins, & Rusiniak, 1974). Likewise, food-caching corvids outperform non food-caching corvids on spatial operant conditioning tasks, but not on non-spatial operant conditioning tasks (e.g., Olson, Kamil, Balda, & Nims, 1995). It is thus not the case that they are good at "associative learning" in general; rather, they appear to have specialized spatial memory skills that non food-caching species lack.

There is no experimental evidence for generic, computer-like learning abilities either. For example, while Marcus et al. (1999) suggested that infants may learn repetition-based structures such as AAB and ABB by representing sequential positions as variables, and discovering relations among such variables, Endress, Dehaene-Lambertz, and Mehler (2007) showed that such repetition-based structures are much easier to learn than other simple structures, and argued that these results are problematic for both statistical and symbolic general-purpose mechanisms. They suggested that such structures are extracted using a specialized mechanism devoted just to detecting repetitions (or identity-relations), even when the repetitions are implemented by different tokens. More generally, they suggested that humans (and presumably other animals) are equipped with a toolbox of highly specialized computational mechanisms that may allow learners to acquire certain generalizations (such as repetition-based structures) particularly easily. They further argued that such

mechanisms may often derive from pre-existing perceptual or memory mechanisms. Below, we will call such mechanisms "perceptual or memory primitives" (POMPs). Before giving more precise definition of such primitives, however, we will give examples of important perceptual constraints in language acquisition that would *not* qualify as POMPs.

### Perceptual or memory primitives

It has long been recognized that perceptual factors are important for language acquisition (e.g., Gleitman & Wanner, 1982; Morgan & Demuth, 1996; Slobin, 1973, 1985). For example, grammatical morphemes in salient positions are acquired earlier than morphemes that do not appear in such positions (e.g., Hsieh, Leonard, & Swanson, 1999; Johnston, 1991; Peters & Strömqvist, 1996). Likewise, grammatical constructions such as the use of auxiliaries or root infinitives are more prominent in child-language if the corresponding constituents appear in salient positions (e.g., Furrow, Nelson, & Benedict, 1979; Gleitman, Newport, & Gleitman, 1984; Newport, Gleitman, & Gleitman, 1977; Wijnen, Kempen, & Gillis, 2001).

These results have in common that perceptual factors enhance the learning of regularities that are unrelated to the perceptual factors themselves. For instance, placing auxiliaries in salient positions facilitates their acquisition. The reason why auxiliary constructions can be acquired at all, however, is that children have a mechanism that

lets them acquire such constructions. The perceptual advantage for auxiliaries in salient positions thus does not explain why such constructions can be acquired in the first place; rather, it just modulates the ease with which other learning mechanisms can operate.[1]

The situation for POMPs is different. For example, repetition-based structures are particularly easy to learn because we have a "repetition-detector." That is, repetitions are salient because learners are equipped with the appropriate POMP that can detect such relations. In other words, the existence of this POMP determines what kinds of structures can be acquired particularly easily, and does not simply modulate how well structures can be learned that are processed through other mechanisms. More generally, we suggested that the language faculty may have recycled computational mechanisms that are used for specific purposes in perception and memory. This is not to say that language can be acquired through "domain-general" mechanisms (whatever these may be); rather, we suggested that certain specific aspects of grammatical structure may take the form they take because the language faculty could rely on phylogenetically pre-existing POMPs that could be adopted for grammatical purposes.

The use of phylogenetically pre-existing abilities for the purposes of communication has been observed for other species' vocalizations. For example, in certain frog species, males emit a

vocalization that females find particularly attractive; however, females were receptive to this vocalization even *before* males evolved the capacity to produce it (as can be shown through playback experiments; see e.g. Ryan, 1998; Ryan, Phelps, & Rand, 2001). Hence, the pre-existing perceptual abilities of females shaped the vocal repertoire of males in subsequent species, as males gained more reproductive success by evolving production capacities that exploited the females' perceptual sensitivities. In the case of POMPs, we suggest that the language faculty made use of certain kinds of structures because pre-existing perceptual and memory abilities made it particularly easy to learn these structures, just as it was advantageous for male frogs to exploit the females' pre-existing sensory capacities. After these pre-existing abilities were used by the language faculty, they may have been deployed in the service of domain-specific, in particular linguistic, computations.

A POMP that is particularly relevant to the current paper concerns the types of *positional* regularities that humans can extract. Take inflectional morphology as an example. In English, for instance, the regular past-tense is formed by adding the /-ed/ morpheme to the *end* of words. This is by no means an idiosyncratic property of English: in most languages, when morphemes such as the /-ed/ suffix are added to words, these are, with a few exceptions, added either at the beginning or at the end of a word (e.g., Greenberg, 1957; Julien, 2002). The same generalization holds for, say, stress assignment.

Stress is either word-initial (as in English), word-final (as in French), or falls on another syllable that is counted from one of the word-edges (as in Italian, where stress generally falls on the second syllable from the last); no language places stress on positions that are not defined relative to the edges (e.g., Halle & Vergnaud, 1987; Hayes, 1995).

More generally, the following generalization seems to hold (we will give more examples in the General Discussion): regularities in natural languages that appeal to the *positions* of items inside constituents of various kinds tend to be defined relative to the *edges* of these constituents (Endress, Nespor, & Mehler, in press). We suggest that it is possible to make sense of this generalization if language learners use a POMP for these grammatical purposes that allows them to encode the positions of items. Specifically, much research on short-term memory has revealed the same constraints on memorizing the positions of elements in sequences as those found in natural languages: sequential positions seem to be encoded relative to the sequence-edges (see below for more details). Hence, if the same kind of POMP is used for remembering the positions of items in a sequence and for the grammatical purposes mentioned above, one can explain why most positional regularities in natural languages are defined relative to the edges of some constituents.

To see this point, it is important to distinguish between memory for *items* and memory for positions. The two seem to be at least partially independent. For instance, a common performance error in

recall experiment is to recall an item in its correct position – but in another sequence than the one where it originally appeared. Apparently, items can thus get linked to sequential positions in a way that is independent of any particular sequence; in other words, items can get marked for the abstract positions they appear in (e.g., Conrad, 1960; Hicks, Hakes, & Young, 1966; Schulz, 1955). It is now well established that participants learn much more reliably that items occur in edge positions than in non-edge positions (e.g., Conrad, 1960; Henson, 1998, 1999; Hicks et al., 1966; Ng & Maybery, 2002; Schulz, 1955). Accordingly, most contemporary models of positional codes in sequences assume, in some form or another, that only edges have proper positional codes, and that internal positions are encoded with respect to the sequences edges (e.g., Henson, 1998; Hitch, Burgess, Towse, & Culpin, 1996; Ng & Maybery, 2002). While the specific implementations vary widely, all models have conceptually in common that there are special edge codes to which items get linked. (We call these codes special because they may exist only for edges but not for other positions.) In Henson's (1998) model, for instance, the activity of a "start" marker decreases during a sequence, while the activity of an "end" marker increases; their relative strengths indicate the position of an item in that sequence. This allows edge positions to be encoded very accurately, but non-edge positions would be encoded less well. If language uses a similar, edge-based mechanism to encode positions, one would expect linguistic regularities to involve

predominantly items in edge-positions of constituents rather than items in other positions, and, as mentioned above, this is exactly what is found across the world's languages.

Note that such a view of sequential positions constrains in important ways just how variable-like positions can be. Recall that Marcus et al. (1999) suggested that positions act as variables, and that infants have a way to discover relations among such variables to learn repetition-based structures. However, if only edges have proper positional codes, then only edge-positions (and maybe positions close enough to the edges) may act in a variable-like way. This seems indeed to be the case, as even adult learners generalize structures defined by the position of repetitions much better when the repetitions are located in sequence-edges as opposed to other positions (Endress, Scholl, & Mehler, 2005). Hence, also in the case of repetition-based structures, edges seem to be the only positions that can be encoded reliably. This is not to say that edges are not symbolic representations, but, in contrast to approaches that treat all positions as formally equivalent variables, only the representations of edges but not of other positions acts as a variable-like slot.

In sum, the POMPs investigated here may be used for linguistic purposes, but may have originated in other perceptual or memory systems, and may then have come to be recycled for linguistic purposes. This view is roughly in line with Hauser, Chomsky, and Fitch's (2002) proposal that only some computations used by the

language faculty are truly language-specific, and that others can also be found in other domains. Once this "computational recycling" of the pre-existing capacities took place, the POMPs may not be limited to purely "perceptual" computations. In fact, in the General Discussion, we will argue that each level of the prosodic and syntactic hierarchies may have their own systems that encode positions. Hence, the POMPs may be used for more abstract computations than what they were originally used for; the underlying computational mechanisms may nevertheless be similar.

Another way to look at POMPs is to consider them as Gestalt-like computational principles. As such, they are largely descriptive, and do not explain *why* the Gestalt principle take the form they take. This, however, is a general problem when describing the behavior of organisms: *ultimate* explanations (that is, the selective pressures that made a behavior advantageous) are not necessarily identical with *proximate* explanations (that is, the mechanisms that enable an organism to exhibit a behavior). Here, we are concerned exclusively with the proximate reasons for which certain regularities can be learned more easily than others. Certain classes of regularities may be particularly easy to learn (and particular prominent) because the relevant computational mechanisms could be recycled from other domains, even though we may never find an ultimate explanation for these mechanisms.

### Phonotactic constraints

In the experiments presented below, we attempt to provide another case study for the importance of edges in regularities that seem more relevant to natural languages than those studied previously. Specifically, we ask whether edge-based, positional codes may be important also for the acquisition of "phonotactic" constraints.

The phonotactic constraints of a language determine the permissible phoneme sequences. These constraints differ across languages. For example, while words in languages like Croatian and Polish can have long consonant clusters, languages like Japanese do not admit any consonant clusters (except N+Consonant). Moreover, when Japanese speakers are presented with new words containing consonant clusters, they perceive (illusory) "filler" vowels between the consonants (e.g., Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Dupoux, Pallier, Kakehi, & Mehler, 2001); for example, when presented with the non-word "ebzo", they perceive the non-word "ebuzo." Phonotactic constraints thus influence profoundly how speech sounds are perceived.

Human infants and adults can learn phonotactic-like regularities from very limited exposure (Chambers, Onishi, & Fisher, 2003; Onishi, Chambers, & Fisher, 2002; Saffran & Thiessen, 2003). In Chambers et al.'s (2003) experiments, for example, participants were presented with CVC (Consonant-Vowel-Consonant) words, and had to learn that the consonants from one set could occur only in word-

onsets, and the consonants from another set only in word-offsets. The sets were arbitrary, and do not play any role in natural languages. For example, they had to learn that the consonants in set {b, k, m, t, f} had to occur in onsets, and the consonants in set {p, g, n, tʃ, s} in offsets.

These results can be explained in different ways. Like the syllables in Marcus et al.'s (1999) experiments, the phoneme positions could have been represented as a sequence of variables XYZ that can be filled with members of the classes of consonants occurring in each of the positions (for example, X ∈ {b, k, m, t, f}). Although these authors did not argue for such a general interpretation, we focus here on the nature and generality of the underlying computations, and thus start from the hypothesis outlined above. We thus ask what kinds of mechanisms participants use when they have to generalize the permissible positions of items (such as the consonants in our and the previous experiments).

In CVC-words, participants could have learned that words could start and end with certain consonants. In other words, the crucial consonants were in the word-edges (i.e., onsets and offsets). As mentioned above, there is ample evidence from the memory literature that it is much easier to remember that items occurred in edge positions than in other positions, because only edges (but not other positions) may have proper *positional codes.* As participants have to generalize in our (and the previous) experiments the permissible *positions* of consonants, they may thus learn such

constraints better in edge positions than in other positions. In contrast, if participants were endowed with a general monolithic symbol-manipulation mechanism, any position should be as good as any other, because the positions would be precisely the variables among which relations should be discovered. Participants thus should learn such constraints regardless of whether the corresponding consonants are located in edge positions or not.

### The current experiments

To explore whether participants can learn phonotactic regularities regardless of the position within words in which they appear, or whether the generalizations depend on the critical consonants being in edge positions, we asked whether participants would learn that the consonants $C_1$ and $C_2$ had to belong to distinct consonant sets not only in items of the form $C_1$VccV$C_2$ (with the critical consonants in edge positions; Experiment 1a) but also in cV$C_1C_2$Vc items (with the critical consonants in middles; Experiment 1b); small c's are filler consonants without particular constraints.

To anticipate our results, participants learned the phonotactic constraints when the critical consonants were in the word edges, but not when they were in word-middles. In Experiment 2, we asked whether participants would generalize similar constraints also in middles when the critical consonants came from natural consonant classes (such as stops and fricatives), as opposed to the arbitrary consonant sets used in Experiments 1a and 1b. Finally, Experiments

3a and 3b asked whether the participants' failure to learn the word-medial phonotactic constraints was due to problems processing word-medial consonants. In these experiments, participants just had to *discriminate* words that differed either in their edge consonants, or just in their middle consonants. If difficulties in generalizing word-medial constraints resulted from difficulties in processing word-medial consonants, participants should be impaired also when just discriminating words that differ only in their medial consonants.

## Experiment 1a: Phonotactic constraints in word-edges

### Materials and Methods

The design of Experiment 1a is shown in Figure 1. Participants heard words of the form $C_1$VccV$C_2$. Participants in group 1 had to learn that $C_1$ had to be a member of the class {k, t, f} ("set 1"), and that $C_2$ had to be a member of the class {s, ʃ, p} ("set 2"). The classes were interchanged for group 2. All clusters that can be formed by these sets are legal in French in both directions, do not resyllabify in intervocalic positions (Dell, 1995), and do not undergo voicing assimilations.

The other consonants could be l, ʁ or n (the "filler set"); each consonant could occur only once in each word. All clusters that can be formed with the filler consonants are legal in French, do not resyllabify in intervocalic positions and do not undergo voicing assimilations.

We will call the consonants in the word-edges the *frame* and the word-medial consonants the *cluster*. Sets 1 and 2 yield nine frames, and the filler set six clusters (excluding repeated consonants). Six frames were selected for familiarization, and three for test (f…s, k…ʃ and t…p and their inversions). All clusters (which, being word-internal, were irrelevant for the generalizations) were used both during familiarization and during test.

We used two vowels that were presented in different orders during familiarization and during test: Familiarization words had the form $C_1$/a/cc/i/$C_2$, and (legal) test items the form $C_1$/i/cc/a/$C_2$, yielding 36 familiarization words, and 18 *legal* words during test. All words were synthesized using the *fr2* voice of MBROLA (Dutoit, Pagel, Pierret, Bataille, & van der Vreken, 1996), and presented over headphones. Participants were tested individually using a PERL/Tk script.

Participants

Sixteen native speakers of French (12 females, mean age 27.2, range 19--45) took part in the experiment. In all experiments, participants were randomly assigned to either group such that “legal” test items for one group were foils for the other group and vice-versa.

Familiarization

Participants were informed that they would hear Martian words. They were instructed to listen to how these words sounded, and were informed that they would have to judge afterwards whether new

words sounded like Martian words. Participants were then presented once with all 36 familiarization words in random order. The list of familiarization items is given in Appendix A.

Test

Before test, participants were informed that they would hear word pairs, and were instructed to choose the word they thought to be in Martian.

Participants were then presented with word pairs. One word was like a familiarization word except that (i) the three frames reserved for test were used and (ii) the vowel [i] was followed by [a] (see Figure 1). We inverted the vowels to make sure that we used new syllables and phoneme combinations during test.

The second word of a pair was identical to the first one except that the frame consonants were inverted; legal items for group 1 were thus foils for group 2 and vice versa. For group 1, for example, /**f**iRla**s**/ was a legal test item, while /**s**iRla**f**/ was a foil. Each of the 18 test pairs was presented twice with different word orders. The list of test pairs is given in Appendix B.

## Results and discussion

As shown in Figure 2, participants generalized the phonotactic constraints to new frames (percentage of correct responses: $M$ = 65.8%, $SD$ = 15.6%), $t(15) = 4.04$, $p = 0.001$, Cohen's $d = 1.0$, $CI_{.95}$ = 57.47%, 74.13%. (Statistical tests are two-tailed throughout this article. T-tests are reported with respect to a chance level of 50%.)

There was no difference between the groups participants were assigned to, $F(1,14) = 0.4$, $p = 0.524$, ns. In other words, participants tracked which consonants could occur word-initially and word-finally, respectively.

### Experiment 1b: Word-medial phonotactic constraints

#### Materials and Methods

Experiment 1b was like Experiment 1a except that the roles of the frames and the clusters were interchanged. Participants had to learn constraints on *word-medial* clusters, while the word-frames were irrelevant to the generalizations; they had to learn that $C_1$ and $C_2$ had to belong to distinct classes in words of the form c/a/$C_1C_2$/i/c. Importantly, the consonants in the word-medial clusters always belonged to different syllables and never resyllabified; as in Experiment 1a, the constraints thus involved single consonants. Sixteen native speakers of French (six females, mean age 21.3, range 18--25) took part in the experiment. The resulting familiarization items and test pairs are listed in Appendices C and D, respectively.

#### Results

As shown in Figure 2, most participants failed to generalize the phonotactic constraints to new clusters ($M = 51.9\%$, $SD = 10.7\%$), $t(15) = 0.7$, $p = 0.485$, Cohen's $d = 0.18$, $CI_{.95} = 46.2\%, 57.6\%$, ns. There was no difference between the groups participants were assigned to, $F(1,14) = 0.5$, $p = 0.493$, ns. Participants in Experiment 1a performed better than participants in Experiment 1b, $F(1,30) = 8.6$,

$p < 0.007$, $\eta_2 = 0.223$.

## Discussion

Participants generalized the phonotactic-like constraints with the critical consonants in edge positions, but not with the critical consonants in word-middles. These results fit well with the view that sequential positions are encoded relative to the sequence-edges (e.g., Henson, 1998; Hitch et al., 1996; Ng & Maybery, 2002); if so, it should be easier to remember which consonants can occur in word-edges than to remember which consonants can occur in word-middles. As such models are usually tested on sequences of individuated items (e.g., words or letters), they should thus apply more to the entire sequence of familiarization words than to the phonemes within a word. However, our results suggest that the encoding of positions *within* words may also be similarly constrained: Phonemic positions may be encoded relative to the word-edges.

In contrast, our results are inconsistent with the view that all phoneme positions act as formally equivalent *positional variables*, that is, like registers in a digital computer. If they did, an operation that can be applied to one variable should also be applicable to the other variables; the generalizations, in contrast, were observed only with one set of "variables," namely in edges but not in middles.

It should be noted that our results do not imply that relations among adjacent consonants are harder to learn than relations among non-adjacent consonants. Indeed, in words of the form CVCCVC, the

two middle consonants are adjacent, while the two edge consonants are not. However, participants did not need to learn any relation among consonants at all; rather, they just had to remember the *positions* in which each consonant could occur. Moreover, even if participants had learned relations among consonants (e.g., that [k] and [s] can occur in the same word), this would not have allowed them to discriminate "legal" items from foils, as we used *new* consonant pairs during the test phase that had not been heard during familiarization. Hence, it seems that participants could learn the positions of consonants (as long as these were in the word-edges) without relying on any adjacent or non-adjacent relation between particular consonants.

One may also ask whether the structures used in Experiments 1a and 1b were indeed comparable. Several considerations suggest that this was the case. First, all familiarization words and test items were legal in French (Dell, 1995). Second, one may have the impression that participants had to learn different kinds of regularities in middles and edges: The regularity in Experiment 1a was carried by single consonants in the edges, while the regularity in Experiment 1b entailed two adjacent middle consonants. However, the middle consonants always belonged to different syllables and never resyllabified. Hence, also in Experiment 1b, participants had to learn regularities entailing the end of one syllable and the onset of another one.

A plausible (temporary) conclusion from these experiments is that certain generalizations in edges are more flexible than in middles. Below, we will interpret this result as evidence for a "perceptual or memory primitive" that assigns special positional codes to edges, and thus makes positional generalizations (such as the ones investigated here) easier in edges than in middles; before, however, it is necessary to rule out a certain number of possible confounds.

## Experiment 2: Word-medial phonotactic constraints with natural classes

In the preceding experiments, sets 1 and 2 were arbitrary consonant sets that do not play any role in natural languages. It is therefore possible that participants might rapidly learn phonotactic-like constraints even in word-middles when these involve natural classes.

### Materials and method

Experiment 2 was identical to Experiment 1b, except that participants had to learn other consonant classes. Instead of the arbitrary classes {k, t, f} and {s, ʃ, p}, we used sets of stops {k, t, p} and fricatives {s, ʃ, f}. All clusters that can be formed with these sets are legal in both directions in French, and do not undergo voicing assimilations. We reserved the clusters /kʃ/, /tf/ and /ps/ (and their inversions) for test. All familiarization items and test pairs are shown in Appendices E and F, respectively.

Sixteen native speakers of French (8 females, mean age 24.5,

range 19--34) took part in the experiment.

## Results

As shown in Figure 3, participants generalized the phonotactic constraints to new frames ($M$ = 61.1%, $SD$ = 17.2%), $t(15) = 2.6$, $p$ = 0.021, Cohen's $d$ = 0.65, $CI_{.95}$ = 52.0%, 70.3%. There was no difference between the groups participants were assigned to, $F(1,14) = 1.1$, $p$ = 0.309, ns. Performance in Experiment 2 was not different from Experiment 1a, $F(1,30) = 0.65$, $p$ = 0.426, $\eta^2$ = 0.0213, ns, and tended to be marginally better than in Experiment 1b, $F(1,30) = 3.3$, $p$ = 0.0785, $\eta^2$ = 0.0996, ns.

## Discussion

In Experiment 2, participants generalized phonotactic-like regularities also in word-middles. The crucial difference between Experiments 1b and 2 --- the use of *natural classes* instead of arbitrary consonant sets --- might have led to very different kinds of processing. Participants might have learned the relative order of the corresponding features [+fricative] and [+stop], for example using directional associations, for which there is ample evidence (e.g., Saffran et al., 1996). Alternatively, a [+fricative][+stop] cluster may be more *similar* to another [+fricative][+stop] cluster than to a [+stop][+fricative] cluster, and participants could thus have matched the test items to the familiarization items by similarity.[1]

Still another possibility may be that participants may simply

have heard more instances of the regularity in Experiment 2 than in Experiment 1b, because all familiarization words conformed to the regularity based on natural classes. This may be so, but this possibility highlights two points. First, the advantage for using natural classes can be explained only because participants had spontaneous biases to process natural classes differently from arbitrary ones.[3]

Secondly, although we obviously cannot (and do not wish to) disprove that participants may learn constraints with arbitrary classes in middles under some conditions, for example with more training, generalizations were readily observed in edges under the current conditions. We thus believe that our experiments are optimized for isolating the role of the edges. Indeed, long familiarizations may allow participants to use other mechanisms to generalize, such as non-adjacent associations between the phonemes in edges and the phonemes in middles. This conclusion is also supported by other experiments. Endress and Bonatti (2007) investigated the time course of positional regularities and associations among items. Although they did not cast their experiments in these terms, participants had to learn that certain syllables (rather than consonants as in the current experiments) had to occur in edges, but they could also learn associations among syllables. Their results suggest that the edge-based regularity was learned very quickly, with little (or no) improvement after the first two minutes of familiarization;

associations among syllables, in contrast, took more time to build up, and were strengthened with more exposure. Hence, positional regularities seem to be learned readily and quickly in edges, while middles require additional manipulations (such as the possibility to form associations among phonetic features).

Experiments 1 and 2 may also clarify other conflicting data. While Chambers et al. (2003) found generalizations with arbitrary classes in 16.5 month-olds, Saffran and Thiessen (2003) found that 9 month-olds generalized phonotactic regularities only with natural classes (Experiments 1b and 2), but not with arbitrary classes. As mentioned above, Chambers et al. (2003) familiarized their participants with CVC words in which the first and the last consonant had to belong to different consonant sets. Saffran and Thiessen (2003), in contrast, familiarized infants with CVCCVC words; in these words, onsets and codas (that is, offsets) of syllables obeyed distinct rules. In their Experiment 1b, syllables began with a unvoiced stop and ended with a voiced stop (or vice versa, depending on the group an infant had been assigned to); in Experiment 2, in contrast, infants had to lean that onsets and codas had to belong to mixed sets of voiced and unvoiced stops (that is, an unnatural rule).

In addition to age and other procedural differences, one important difference between Chambers et al.'s (2003) and Saffran and Thiessen's (2003) was that Saffran and Thiessen (2003) used longer words in which the crucial consonants were (at least partly) in

word-middles. Even though the differences in the infants' age and in the procedure may make these experiments only partially comparable, our results suggest another natural explanation for the discrepancy between these results, namely that generalizations in edges are more flexible than in middles and, as we will argue below, that they may employ other mechanisms. In edges, it may be possible to learn rather arbitrary positional regularities, while generalizations in word-middles may tend to rely on other mechanisms that may require additional cues such as natural classes.

### Experiment 3a: Processing of consonants in word-edges

Experiment 2 showed that participants can generalize at least some regularities in word-middles; it is thus unlikely that the failure in Experiment 1b was due to overall psychophysical difficulties (that is, that participants may simply not perceive middle consonants). Experiments 3a and 3b examined processing difficulties for word-middles in another way. In these experiments, participants had just to discriminate words that differed either in their edge consonants (Experiment 3a) or in their middle consonants (Experiment 3b); if the failure in Experiment 1b was due to processing difficulties for middle consonants, these should also be observed in a discrimination experiment.

#### Materials and method

After the same familiarization as in Experiment 1a (where participants were not told that they would just have to discriminate

items, but were instructed to find out how Martian words sounded), participants were informed that they would hear pairs of Martian words, and that they would have to decide whether the words in a pair were identical or different. Pairs were constructed by presenting the "legal" test items from Experiment 1a twice, once with themselves and once with the foil they had been presented with in Experiment 1a. Hence, participants had to make the same distinctions as before, but without the need to generalize the phonotactic-like constraints. Eighteen native speakers of French (12 females, mean age 24.7, range 18--34) took part in the experiment.

Results

Figure 4 shows that participants were almost perfect in discriminating words differing in the order of their edge consonants ($M$ = 98.1%, $SD$ = 3.7%), $t(17) = 55.4$, $p < 0.0001$, Cohen's $d = 13$, $CI_{.95}$ = 96.3%, 100.0%; there was no difference between the groups participants were assigned to, $F(1,16) = 1.14$, $p = 0.301$, ns.

**Experiment 3b: Processing of consonants in word-middles**

Experiment 3b was identical to Experiment 3a except that participants had to discriminate words that differed only in their middle consonants

Materials and method

After the same familiarization as in Experiment 1b (where participants were not told that they would just have to discriminate items, but were instructed to find out how Martian words sounded),

participants were informed that they would hear pairs of Martian words, and that they would have to decide whether the words in a pair were identical or different. Pairs were constructed by presenting the "legal" test items from Experiment 1b twice, once with themselves and once with the foil they had been presented with in Experiment 1b. Hence, participants had to make the same distinctions as before, but without the need to generalize the phonotactic-like constraints. Eighteen native speakers of French (12 females, mean age 22.7, range 18-35) took part in the experiment.

## Results

Figure 4 shows that participants were almost perfect in discriminating words differing only in the order of their medial consonants ($M$ = 95.7%, $SD$ = 4.8%), $t(17) = 40.5$, $p < 0.0001$, Cohen's $d = 9.5$, $CI_{.95}$ = 93.3%, 98.1%; there was no difference between the groups participants were assigned to, $F(1,16) = 0.66$, $p = 0.428$, ns. An ANOVA with factors position (edge vs. middle, that is, Experiment 3a vs. 3b) and language yielded neither a main effect of position, $F(1,32) = 3.0$, $p = 0.094$, $\eta^2 = 0.081$, ns, nor of language, $F(1,32) = 1.7$, $p = 0.205$, $\eta^2 = 0.046$, ns, nor an interaction between these factors, $F(1,32) < 0.1$, $p > 0.999$, $\eta^2 = 0$, ns.

## Discussion

In Experiment 3a and 3b, participants were near perfect at discriminating words that differed either in their edge consonants or in their middle consonants. If consonants were simply harder to process

in word-middles than in word-edges, the problems for processing word-internal consonants should also be observed when no generalizations are required. This suggests that there is no intrinsic difficulty for processing word-internal consonants. This conclusion is not confounded by a ceiling effect in Experiments 3a and 3b either. Indeed, if participants had processing difficulties for middle consonants, they would not be at ceiling in the first place.

Conceivably, one may argue that, even in the discrimination experiments, there was a marginal edge advantage, and that other manipulations (such as presenting the items in noise) may increase the difference between edges and middles also for discrimination tasks. However, when presenting the discrimination task and the generalization task without any particular manipulation to make these tasks hard, discrimination performance is at ceiling both in edges and middles, while generalization performance is at chance in middles. Thus, even if one is willing to accept an edge advantage for processing consonants (which is rather likely after all), this slight edge advantage is unlikely to be the only explanation for the break-down of generalizations in middles; if it were, one would expect the difference between Experiments 1a and 1b, and between Experiments 3a and 3b to be comparable. However, in terms of effect sizes, the difference between Experiments 1a and 1b was almost twice as large as the difference between Experiments 3a and 3b (Cohen's $d$ = 1.04 and 0.58, respectively). Of course, one can argue that even a minimal

perceptual problem can be magnified when it feeds into further processes. However, this requires that participants were actually impaired in the word discrimination task when the crucial difference between words was located in word middles --- where they were at ceiling. Hence, while it is likely that also some difficulties for processing middle consonants contributed to the failure in Experiment 1b, we believe that the most plausible conclusion is that at least parts of the failure must be attributed to other reasons than a brute impairment for processing middle consonants, and thus to processes responsible for the generalizations.

Maybe the memory demands in Experiment 1b were higher than in Experiment 3b. While conceivable, this explanation seems incorrect. In fact, participants could not have memorized all 36 familiarization examples; they may certainly keep a few items in memory (as they have to do also in Experiment 3b), but building a "corpus" of example words to extract the generalizations would probably exceed the participants' memory capacity. In any case, during familiarization, participants had equal reason to memorize the items both in the generalization and in the discrimination experiments --- because they were not told that they just had to discriminate items. Moreover, even if they had memorized them, it would not have allowed them to generalize the phonotactic constraints, since we used new items during test that did not share any phoneme combinations with the familiarization items. For generalizing the constraints, they

just had to remember which consonants occurred in specific positions.

As discussed in the Introduction (and in more detail in the General Discussion), a more abstract memory advantage for positional memory may explain the different results in Experiments 1a and 1b, namely that *positional codes* are available only for edges. Indeed, a serial position effect for memory for abstract positions (e.g., memory that a given phoneme appeared in, say, the third position in a sequence) may make positional knowledge in medial positions less accurate than in edge positions, which may explain the edge advantage we observed --- since the constraints participants had to learn were fundamentally positional regularities. As item memory and positional memory are at least partially independent, discrimination in middles may be perfect while positional information in middles may be deficient. Here, we just note that the failure in Experiment 1b does not seem to result from a brute impairment for processing or memorizing middle consonants, but is due at least in part to intrinsic limitations of the processes computing the generalizations.

## General Discussion

Cognitive processes are often attributed to general-purpose machinery. Some authors take this machinery to be analogous to digital computers (e.g., Anderson, 1993; Marcus, 2001; Newell, 1980), while others favor associationist models such as those implemented by connectionist networks (e.g., Elman et al., 1996; McClelland et al., 1986; Rumelhart et al., 1986; Seidenberg, 1997). In

contrast to these views, some cognitive processes may be specialized and constrained to fulfill particular functions (e.g., Fodor, 1983; Gallistel, 1990, 2000; Hauser, 2000; Hauser et al., 2002; Ramachandran, 1990). In the case of (artificial) grammar learning, for example, Endress et al. (2007) proposed that some simple grammars may be learned by specialized and constrained operations which they dubbed *perceptual or memory primitives* (POMPs). Their point was that, while perceptual constraints are often treated as uninteresting annoyances (but see e.g. Gleitman & Wanner, 1982; Morgan & Demuth, 1996; Slobin, 1973, 1985), certain perceptual and memory mechanisms may have structural properties that make them particularly suitable for learning some grammatical-like regularities. That is, while it has long been a tenet of linguistic theory that language uses specialized and largely domain-specific mechanisms, some of these domain-specific constraints may have their origins based on perceptual or memory systems.

Here, we use phonotactic-like constraints as a case study to ask whether such primitives may support some language-related computations. Participants had to learn that the consonants $C_1$ and $C_2$ had to be members of distinct consonant sets. They learned such regularities in words of the form $C_1$VccV$C_2$ but not in words of the form cV$C_1C_2$Vc. Still, they generalized such constraints also in word-middles when natural consonant classes were used instead of arbitrary ones. The failure to generalize in middle positions with arbitrary

classes cannot be attributed to psychophysical difficulties in such positions since participants can *discriminate* perfectly well words that differ only in their medial consonants.

Why are edges favored?

What may be the reason for the edge advantage? As discussed in the Introduction, our results are consistent with the conclusion from research on short-term memory that learners can encode the *positions* of items in a sequence, and that such positions are encoded relative to the sequence-edges. That is, while these models of sequential memory are usually applied to sequences of individuated items such as words and letters, our results suggest that the encoding of positions *within* words may be similarly constrained: the positions of phonemes within words may also be encoded relative to the word-edges.

It is worth stressing again that such knowledge of sequential positions, for example that [p] was in position 2, is distinct (and probably independent) from order relations, for example that [p] occurred before [f] (see e.g. Henson, 1998, for a review). As such positional knowledge is precisely what defines the generalizations in our experiments, the same constraints that have been uncovered in the context of sequential memory also seem to apply in the context of the phonotactic generalizations. Participants learn the positions of items much more reliably in edge positions than in non-edge positions (e.g., Conrad, 1960; Henson, 1998, 1999; Hicks et al., 1966; Hitch et al., 1996; Ng & Maybery, 2002; Schulz, 1955), probably because exact

positional codes may be available only in edges (while all other positions are encoded relative to the sequence-edges).

We thus suggest that the phonotactic constraints are learned through the same kinds of mechanisms that are used for encoding positions in sequences, namely by linking the critical consonants to edge-based, positional codes. These codes may allow participants to learn which consonants can occur in word onsets and offsets, respectively, but not which consonants can occur in other positions. In other words, the positions of non-edge consonants may be much harder to identify, at least for longer words, because they may be defined with respect to the word-edges as anchor points. The further a position is from the edges, the harder it should be to encode it. This also suggests that the ability to code for positions may not be an all-or-none property; positions close to edges, for example, may be coded relatively well under some circumstances.

It is important to note that a classical serial position effect is an unlikely reason for the edge advantage for generalizations, as Experiment 2 showed that participants can learn some constraints in word-middles. Moreover, one has to explain why generalization in middles was at chance, while participants discriminated words differing only in their middle consonants as well as words differing only in their edge consonants. Maybe the discrimination experiment was in some sense “easier” than the generalization experiment, but this is exactly the point: under neutral conditions, generalization in

middles was at chance, while discrimination was at ceiling, showing no impairment at all due to the position of the critical consonants. This suggests that, while "performance" factors contributed in all likelihood to our results, they are unlikely to be the *only* explanation of the dramatic generalization deficit in middles. If they were the only explanation, one would not expect the dissociation in the effect of the edges on generalization and discrimination. The same is true for an account that attributes the edge advantage to the "saliency" of the edges. While consonants in edge positions are more salient than in middles, one would not expect the discrimination performance in middles to be at ceiling if middle consonants were so much less salient to yield the breakdown of the generalizations.

It thus seems that the mechanisms computing the generalizations are also inherently constrained --- independently of such "performance" factors. We suggest that the relevant constraint is that proper positional codes may exist only for edges, and that middle positions can be encoded only relative to the edges. If so, some language-related computations may take advantage of such codes.

Edges and artificial grammar learning

In many artificial grammar learning experiments, it has been observed that items in edges are learned particularly well (e.g., Reber & Lewis, 1977; Servan-Schreiber & Anderson, 1990). In such experiments, participants are typically familiarized with consonant strings derived from an underlying grammar; then, they have to judge

whether new strings conform to the underlying grammar or not. Consonants (or consonant bigrams) that occurred in edges are particularly important for the grammaticality judgments. However, the precise role of the edges has remained unclear. On the one hand, and in line with a classic serial position effect, items in edges may simply be memorized better than items in middles. Since the grammaticality judgments in such experiments are usually predicted by the familiarity with the bigrams in the test items (e.g., Cleeremans & McClelland, 1991; Dienes, Broadbent, & Berry, 1991; Kinder & Assmann, 2000), a better ability to memorize items in edges would also predict that items in edges may be more important for grammaticality judgments.

On the other hand, participants may learn the *positions* of items (as in our experiments); if positional information is used for grammaticality judgments, the possibility that only edges seem to have proper positional codes (e.g., Henson, 1998; Hitch et al., 1996; Ng & Maybery, 2002) may make items in edges particularly important for grammaticality judgments. However, bigram information seems to be much more important for grammaticality judgments than positional information (e.g., Kinder, 2000; Perruchet & Pacteau, 1990; Reber & Lewis, 1977). Moreover, such experiments were typically not optimized for separating the influences of proper positional codes and other ways to learn sequences. In such experiments, position information (say, that ‘k’ occurred in the third position in a string) is typically confounded with order information

(say, that ‘k’ follows ‘t’). It is thus unclear to what extent constraints on positional codes determine what kinds of artificial grammars are learned.

In our Experiments 1a and 1b, in contrast, participants could rely only on positional regularities, since bigrams and so forth were simply not shared between familiarization and test items. Hence, our experiments tested the learning of positional information unconfounded with order information. Under these conditions, participants generalized regularities well in edges but poorly in middles (at least with arbitrary classes). As mentioned above, such a result fits well with the conclusion from memory research that proper positional codes are available only in edges while other positions are coded relative to these anchor points. Our results suggest that these codes can be used for drawing certain generalizations.[4]

Natural vs. arbitrary phonotactic constraints in edges and middles

As mentioned above, our results help reconciling conflicting results about what kinds of phonotactic constraints can be learned. Recall that Chambers et al. (2003) observed phonotactic generalizations with arbitrary classes, while Saffran and Thiessen (2003) observed such generalizations only with natural classes. One of the reasons for this discrepancy may be that (at least some of) the critical consonants in the latter experiment were located in word

middles; this suggests that positional generalizations may be particularly flexible in edge positions, and that non-positional cues may predominate for extracting generalizations in other positions. For example, participants may predominantly use associations among items in middles; if so, they could learn natural constraints by forming associations among phonetic features. In edges, in contrast, participants may use positional codes for tagging items for their positions; it may thus be possible to memorize that rather arbitrary sets of items occurred in edges, while similar positional regularities may be more difficult to learn in other positions.

Edges and natural language

The above considerations suggest that items in edge positions can rely on specialized mechanisms coding for their positions. We suggest that this edge-based mechanism is part of the inventory of perceptual or memory primitives, and that certain of these primitives may indeed support linguistic computations. In other words, we suggest that the constraints that determine which sequential positions can be encoded precisely also determine which positional generalizations can be learned. While such operations are probably not among the unique computational capacities that made language possible only in humans, the language faculty may well have recycled preexisting capacities humans share with non-human animals, such as sensitivities to rhythmical (e.g., Ramus, Hauser, Miller, Morris, & Mehler, 2000) or statistical regularities in speech (e.g., Hauser,

Newport, & Aslin, 2001), or to phonemic categories (e.g., Kluender, Diehl, & Killeen, 1987) and coarticulation (e.g., Lotto, Kluender, & Holt, 1997). In other words, while a sensitivity to edge-positions is clearly not specific to language, such a sensitivity may nevertheless be used for grammatical purposes.

As it turns out, edge-based positional codes may link many linguistic observations to psychological processes, and may also ground some abstract linguistic theories in basic psychological mechanisms. As mentioned in the introduction, affixes (such as the /-ed/ affix in walk-ed) typically occur in word-edges. Children may thus not acquire affixation rules only because they have a tendency to attend to edges (Slobin, 1973, 1985), but also because they can encode these positions due to the appropriate positional codes. Likewise, stressed syllables are always defined relative to the word-edges (e.g., Halle & Vergnaud, 1987; Hayes, 1995).

Edges even seem to be important for hierarchical processing. For instance, phonological and morphosyntactic hierarchies are famous for not being identical. Still, in the case of a mismatch between a phonological and a morphosyntactic constituent, at least one of the edges of these constituents is always *aligned* (e.g., McCarthy & Prince, 1993; Nespor & Vogel, 1986). For example, the English plural [s] is a morpheme (in the morphosyntactic hierarchy) but not a syllable (in the prosodic hierarchy); still, the right edge of the morpheme is always aligned with the right edge of a syllable (that

is, these two edge coincide). More generally, numerous linguistic regularities are most easily explained if one assumes that constituents on different levels of different hierarchies have to be aligned (e.g., McCarthy & Prince, 1993).

If this conjecture holds, one may ask why we observed generalization only at word-edges, but not in word-middles; after all, also in the middle condition, the crucial consonants were at *syllable*-edges. Hence, if edges can be tracked at multiple, hierarchical levels, a plausible prediction is that participants should also generalize in the middle condition. Note, however, that not all syllable edges in our experiment provided (positive) evidence for such a regularity. For example, while the onset (and thus the syllable edge) of the second syllable in the middle condition instantiated a phonotactic constraint, the onset of the first syllable did not. Hence, in terms of the phoneme positions within words, participants had consistent evidence for the positional regularity they were supposed to learn in Experiment 1b; for the constraint on syllable edges, in contrast, the evidence was much less consistent. Nevertheless, it is interesting to note that this pattern of results is also reflected in natural languages, where, in many languages, positional constraints are much more idiosyncratic at word-edges than at word-internal syllable-edges (M. Nespor, personal communication). In Italian, for instance, words can end in /s/ but with no other fricative, or in /n/ but with no other nasal. Constraints on word-internal coda consonants, in contrast, typically appeal to natural

classes. Hence, at word-edges, learners may use edge-based positional codes for learning some phonotactic constraints, while they may use other mechanisms in word-middles even if these constraints involve syllable-edges.

Despite its simplicity, a "primitive" that allows to encode edge positions may shed new light on some fundamental and long-standing debates in cognitive science. The most prominent domain where symbolic and statistical approaches have been tested is inflectional morphology, in particular the English past-tense (e.g., Pinker, 1991; Pinker & Prince, 1988; Rumelhart & McClelland, 1986). Indeed, a primitive that is sensitive to word edges may be used for affixation, and our results may be taken as relatively direct evidence for a specific operation that might support affixation. It may thus provide a psychological mechanism for regulars in this debate: Rather than relying on symbolic or statistical general-purpose machinery, an operation making positional codes available in word-edges may be a plausible mechanism of suffixation (see also Slobin, 1973, 1985, for a related proposal). Learning the surface forms involved in affixation may thus recruit similar mechanisms to those uncovered in research about positional memory. If so, one would expect nonhuman animals (who are sensitive to sequential positions; see e.g. Orlov, Yakovlev, Hochstein, & Zohary, 2000; Terrace, Son, & Brannon, 2003) to be able to learn affixation surface forms, and, indeed, cotton-top tamarin monkeys can do so (Endress, Cahill, Block, Watumull, & Hauser,

under review). This being said, just having representations of edges does not allow an animal to link affixation rules to the semantic, phonological and syntactic properties that are crucial to affixation in natural-language morphology. However, the debate on the status of inflectional morphology focused almost exclusively on the acquisition of surface forms, and our results provide a simple mechanisms by which such surface forms can be acquired.

In sum, our results suggest that perceptual constraints cannot always be dismissed as uninteresting performance factors. Rather, some specific constraints may be the very mechanisms by which some possibly language-related generalizations are extracted. While our results suggest that edge-based, positional codes may be important for various linguistic generalizations, it will be important to find out what other POMPs exist, and to understand their precise role for language acquisition and use.

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**Appendix A: Familiarization words in Experiments 1a and 3a.**

| Group 1 | Group 2 | Group 1 | Group 2 |
|---|---|---|---|
| kalRis | salRik | kaRnis | saRnik |
| kalRip | salRit | kaRnip | saRnit |
| talRis | SalRit | taRnis | SaRnit |
| talRiS | SalRif | taRniS | SaRnif |
| falRiS | palRik | faRniS | paRnik |
| falRip | palRif | faRnip | paRnif |
| kalnis | salnik | kanlis | sanlik |
| kalnip | salnit | kanlip | sanlit |
| talnis | Salnit | tanlis | Sanlit |
| talniS | Salnif | tanliS | Sanlif |
| falniS | palnik | fanliS | panlik |
| falnip | palnif | fanlip | panlif |
| kaRlis | saRlik | kanRis | sanRik |
| kaRlip | saRlit | kanRip | sanRit |
| taRlis | SaRlit | tanRis | SanRit |
| taRliS | SaRlif | tanRiS | SanRif |
| faRliS | paRlik | fanRiS | panRik |
| faRlip | paRlif | fanRip | panRif |

**Appendix B: Test pairs in Experiments 1a.**

| Words (Group 1) Foils (Group 2) | Foils (Group 1) Foils (Group 2) | Words (Group1) Words (Group2) | Foils (Group 1) Foils (Group 2) |
|---|---|---|---|
| fiRlas | siRlaf | kilnaS | Silnak |
| fiRnas | siRnaf | kinRaS | SinRak |
| filRas | silRaf | kinlaS | Sinlak |
| filnas | silnaf | tiRlap | piRlat |
| finRas | sinRaf | tiRnap | piRnat |
| finlas | sinlaf | tilRap | pilRat |
| kiRlaS | SiRlak | tilnap | pilnat |
| kiRnaS | SiRnak | tinRap | pinRat |
| kilRaS | SilRak | tinlap | pinlat |

**Appendix C: Familiarization words in Experiments 1b and 3b.**

| Group 1 | Group 2 | Group 1 | Group 2 |
|---|---|---|---|
| laksiR | laskiR | Raksin | Raskin |
| lakpiR | lastiR | Rakpin | Rastin |
| latsiR | laStiR | Ratsin | RaStin |
| latSiR | laSfiR | RatSin | RaSfin |
| lafSiR | lapkiR | RafSin | Rapkin |
| lafpiR | lapfiR | Rafpin | Rapfin |
| laksin | laskin | naksil | naskil |
| lakpin | lastin | nakpil | nastil |
| latsin | lastin | natsil | naStil |
| latSin | laSfin | natSil | naSfil |
| lafSin | lapkin | nafSil | napkil |
| lafpin | lapfin | nafpil | napfil |
| Raksil | Raskil | naksiR | naskiR |
| Rakpil | Rastil | nakpiR | nastiR |
| Ratsil | RaStil | natsiR | naStiR |
| RatSil | RaSfil | natSiR | naSfiR |
| RafSil | Rapkil | nafSiR | napkiR |
| Rafpil | Rapfil | nafpiR | napfiR |

**Appendix D: Test pairs in Experiments 1b.**

| Words (Group 1) Foils (Group 2) | Foils (Group 1) Foils (Group 2) | Words (Group1) Words (Group2) | Foils (Group 1) Foils (Group 2) |
|---|---|---|---|
| Rifsal | Risfal | likSan | liSkan |
| Rifsan | Risfan | litpaR | liptaR |
| RikSal | RiSkal | litpan | liptan |
| RikSan | RiSkan | nifsaR | nisfaR |
| Ritpal | Riptal | nifsal | nisfal |
| Ritpan | Riptan | nikSaR | niSkaR |
| lifsaR | lisfaR | nikSal | niSkal |
| lifsan | lisfan | nitpaR | niptaR |
| likSaR | liSkaR | nitpal | niptal |

**Appendix E: Familiarization words in Experiment 2.**

| Group 1 | Group 2 | Group 1 | Group 2 |
|---|---|---|---|
| laksiR | laskiR | Raksin | Raskin |
| lakfiR | lastiR | Rakfin | Rastin |
| latsiR | laStiR | Ratsin | RaStin |
| latSiR | laSpiR | RatSin | RaSpin |
| lapSiR | lafkiR | RapSin | Rafkin |
| lapfiR | lafpiR | Rapfin | Rafpin |
| laksin | laskin | naksil | naskil |
| lakfin | lastin | nakfil | nastil |
| latsin | lastin | natsil | naStil |
| latSin | laSpin | natSil | naSpil |
| lapSin | lafkin | napSil | nafkil |
| lapfin | lafpin | napfil | nafpil |
| Raksil | Raskil | naksiR | naskiR |
| Rakfil | Rastil | nakfiR | nastiR |
| Ratsil | RaStil | natsiR | naStiR |
| RatSil | RaSpil | natSiR | naSpiR |
| RapSil | Rafkil | napSiR | nafkiR |
| Rapfil | Rafpil | napfiR | nafpiR |

**Appendix F: Test pairs in Experiments 2.**

| Words (Group 1) Foils (Group 2) | Foils (Group 1) Foils (Group 2) | Words (Group1) Words (Group2) | Foils (Group 1) Foils (Group 2) |
|---|---|---|---|
| likSaR | liSkaR | RikSan | RiSkan |
| litfaR | liftaR | Ritfan | Riftan |
| lipsaR | lispaR | Ripsan | Rispan |
| likSan | liSkan | nikSal | niSkal |
| litfan | liftan | nitfal | niftal |
| lipsan | lispan | nipsal | nispal |
| RikSal | RiSkal | nikSaR | niSkaR |
| Ritfal | Riftal | nitfaR | niftaR |
| Ripsal | Rispal | nipsaR | nispaR |

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**Footnotes**

[1] The same conclusion applies to suggestions that children's reduced working memory capacity explains why children are much better at language acquisition than adults (Newport, 1990). In fact, this view makes the prediction that all structures should be equally easy to learn as long as they fit a learners' memory-span. Here, in contrast, we attempt to investigate why some classes of structures are easier to learn than others, based on specific memory *mechanisms*.

[2] This similarity may arise on at least two levels. On the one hand, participants may use the *acoustic* (or perceptual) similarity among fricatives and among plosives; on the other hand, they may also rely on a more abstract similarity in terms of phonetic features. The experiments presented here were not optimized to discriminate between these possibilities. Rather, our point was to show that generalizations in middles are much less flexible than in edges, presumably because they can rely on different mechanisms; while participants could generalize arbitrary regularities in edges, generalizations in middles required additional cues such as the use of natural classes.

[3] The argument that participants may have had more exposure to the regularity with natural classes does not apply if the advantage for natural classes is due to the acoustic similarity of consonants within natural classes, because, in this case, there would be no feature

combination that is always repeated.

[4] Possibly, edge-positions may be particular easy to encode because participants may form associations with the silences preceding and following the edges. This results predicts, however, that generalizations should break down just as in middles if the test items are surrounded by noises or pure tones; this is because participants would have learned that the edges are surrounded by silences during familiarization, but there would not be any silences bordering the words during test. This prediction, however, is not born out (see Endress & Bonatti, 2007, for such an experiment, and other considerations making associations between silences and items in edges an unlikely explanation of the results). While one may argue that, also in the aforementioned control experiment, there is a transition from non-speech to speech (and vice-versa) at the word edges, such an explanation requires postulating specific codes for speech and all stimuli that may not be speech. The edge codes would thus simply be the onsets of these speech/non-speech codes, and even in this case, one would need a way to encode the position of phonemes relative to the onset of these codes. A more plausible conclusion (that is supported by considerable research in the memory literature) is thus that only edges have proper positional codes, while all other positions are coded relative to the edges.

**Figure Captions**

Figure 1: Paradigm of Experiment 1a. (a) With the two sets of 3 consonants {k, t, f} and {s, ʃ, p}, one can form 9 consonant combinations. Of these 9 combinations, 6 were used for familiarization (black phonemes, see b) and 3 were reserved for test (gray underlined phonemes, see c). (b) During familiarization, the 6 consonant combinations were used as "word-frames"; the word-middles were filled with 6 different VCCV fillers (such as 'alʁi'), yielding 36 familiarization words. (c) During test, participants had to choose between words that used the consonant frames that had not been used during familiarization and words in which the consonant frame was inverted. The word middles were filled with the same fillers as during familiarization except that the order of the vowels was inverted. The role of legal items and foils was counterbalanced across participants.

Figure 2: Results of Experiments 1a and 1b. Dots represent averages of individual participants, diamonds represent sample averages, and the dotted line represents the chance level of 50%. Participants learned that the consonants $C_1$ and $C_2$ had to be from distinct classes in words of the form $C_1$VccV$C_2$ (where the critical consonants are located in edge positions; Experiment 1a) but not in words of the form cV$C_1C_2$Vc (where the critical consonants are located in word-middles; Experiment 1b).

Figure 3: Results of Experiments 1a, 1b and 2. Dots represent averages of individual participants, diamonds represent sample averages and the dotted line represents the chance level of 50%. When using arbitrary consonant sets, participants generalized the phonotactic-like constraints only in word-edge (Experiment 1a) but not in word-middles (Experiment 1b). When using natural consonant classes, in contrast, participants readily generalized the constraints also in word-middles (Experiment 2).

Figure 4: Results of Experiment 3a and 3b. Dots represent averages of individual participants, diamonds represent the sample averages and the dotted line represents the chance level of 50%. Participants discriminated items that differed only in the order of their word-medial consonants as well as words that differed in the order of their edge-consonants.

Figure 1:

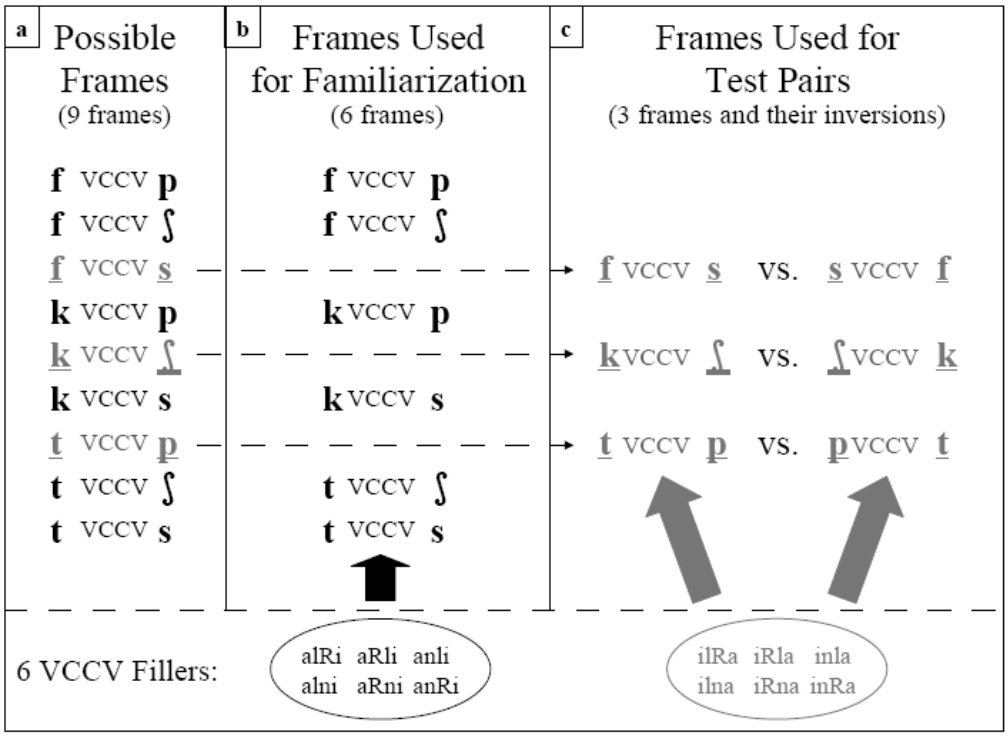

a
Possible Frames
(9 frames)
f VCCV p
f VCCV ʃ
f VCCV s
k VCCV p
k VCCV ʃ
k VCCV s
t VCCV p
t VCCV ʃ
t VCCV s
b
Frames Used for Familiarization
(6 frames)
f VCCV p
f VCCV ʃ
k VCCV p
k VCCV s
t VCCV ʃ
t VCCV s
c
Frames Used for Test Pairs
(3 frames and their inversions)
f VCCV s vs. s VCCV f
k VCCV ʃ vs. ʃ VCCV k
t VCCV p vs. p VCCV t
6 VCCV Fillers:
alRi aRli anli
alni aRni anRi
ilRa iRla inla
ilna iRna inRa

Figure 2:

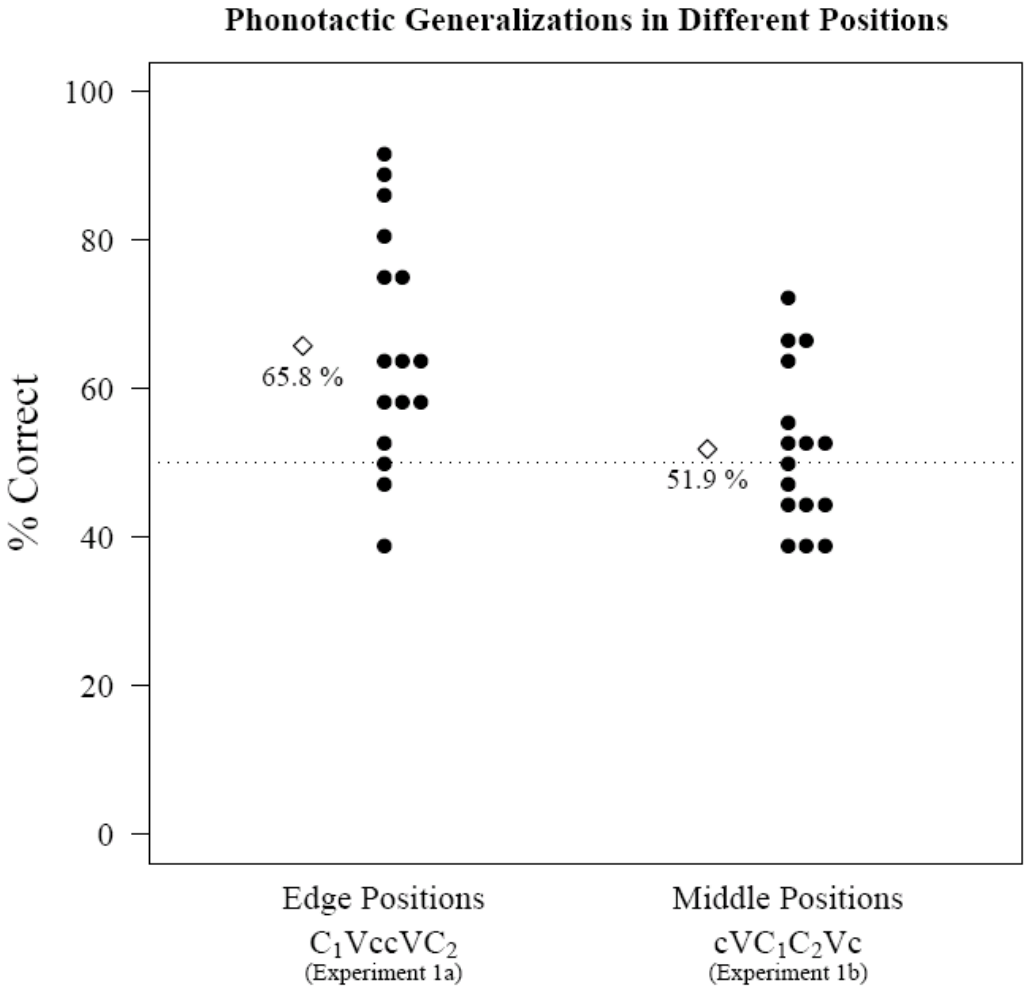

Phonotactic Generalizations in Different Positions
100
80
60
40
20
0
% Correct
65.8 %
51.9 %
Edge Positions
C1VccVC2
(Experiment 1a)
Middle Positions
cVC1C2Vc
(Experiment 1b)

Figure 3:

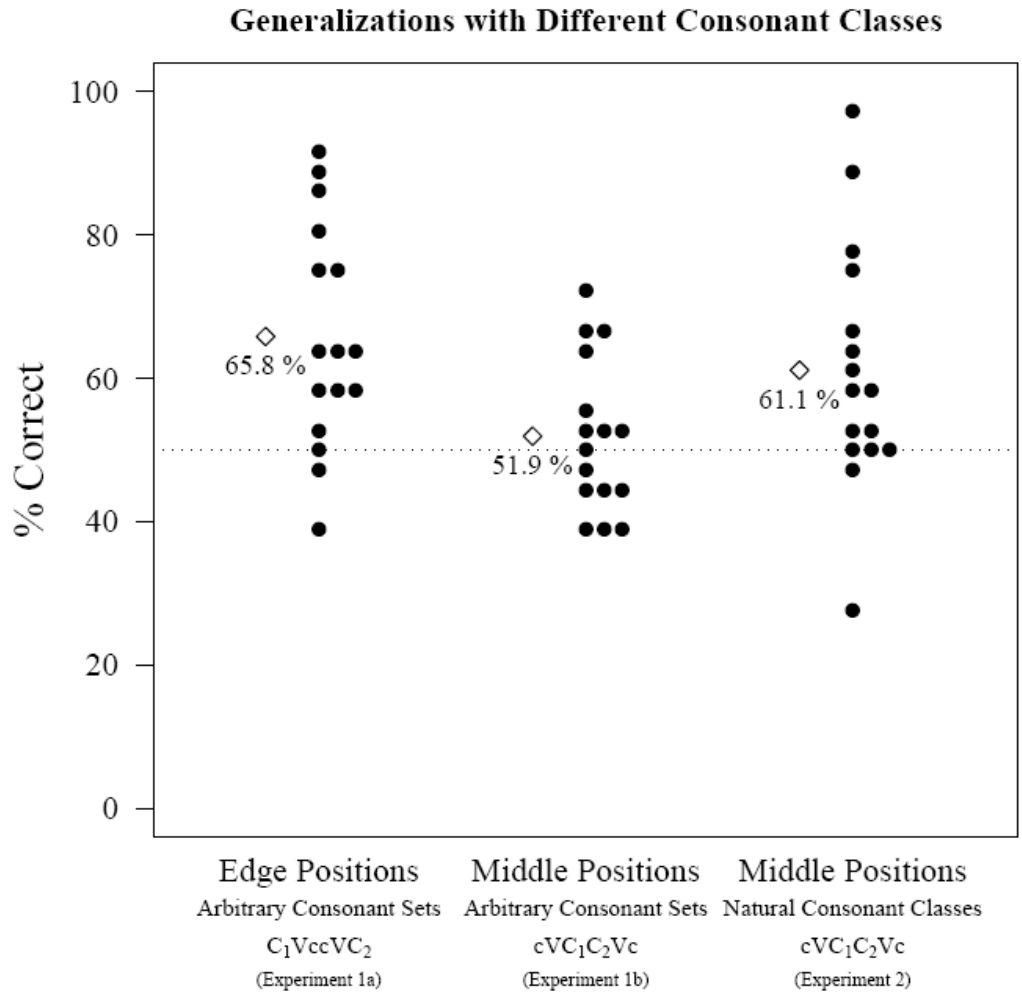
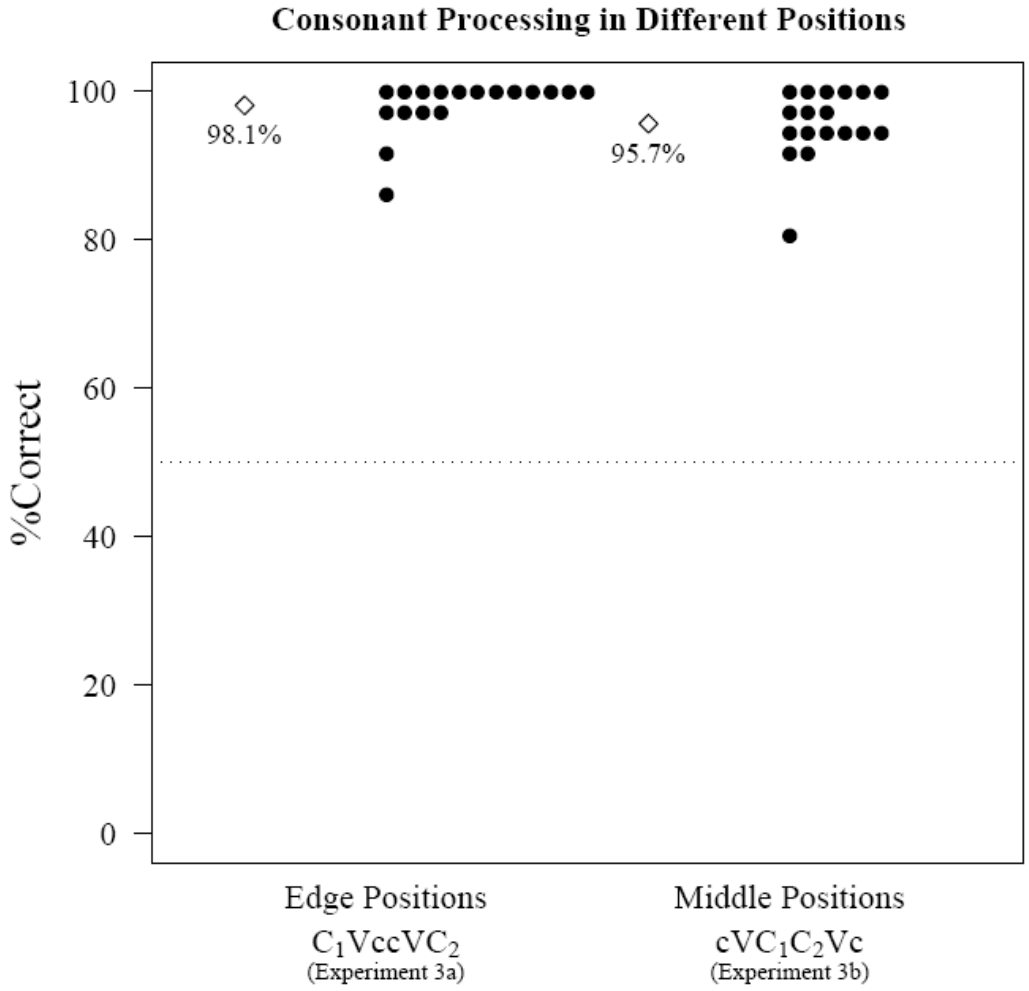

Generalizations with Different Consonant Classes
% Correct
100
80
60
40
20
0
65.8 %
51.9 %
61.1 %
Edge Positions
Arbitrary Consonant Sets
C1VccVC2
(Experiment 1a)
Middle Positions
Arbitrary Consonant Sets
cVC1C2Vc
(Experiment 1b)
Middle Positions
Natural Consonant Classes
cVC1C2Vc
(Experiment 2)

Figure 4:


Consonant Processing in Different Positions
100
80
60
40
20
0
%Correct
98.1%
95.7%
Edge Positions
C1VccVC2
(Experiment 3a)
Middle Positions
cVC1C2Vc
(Experiment 3b)