Cyclic opacity facilitates phonological interpretation

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Cyclic computation has re-emerged in recent years as a core issue [1–3]. Cyclic computation in human language has two key properties: (i) "inside-out-ness": a computation or set of computations is done once for each domain, as defined by the constituent structure, starting from the most deeply nested constituent and working outwards; (ii) "cyclic opacity": the computation for domain n is insensitive to the contents of domain $n-1$, or key parts of it. I offer a proof that cyclic opacity can be seen as a way of accommodating inside-out-ness, taking into account that phonological computations are regular, while syntactic computations are non-regular (mildly context sensitive) [4–9]. I restrict attention to the phonological cycle [10,11], where the opacity facts are best described by a generalization called the Strict Cycle Condition (SCC) [12,13,14]; I provide a formalization of the SCC and demonstrate that the resulting cyclic computation is regular, while a phonological computation satisfying (i) but not (ii) would not be. The SCC is illustrated by the interaction between two Catalan phonological processes shown in (1–5) [13]:

(1) *Glide Formation:* pá i sál → pájsál, "bread and salt": $[+\text{hi}, -\text{stress}] \rightarrow [-\text{syll}] \,/\, [+\text{syll}] \#_0$—

(2) *Destressing (D):* átom+ík → atomík, "atomic": $\text{V} \rightarrow [-\text{stress}] \,/\, \#\#\text{X}$—$\text{Y}\,[+\text{stress}]\,\text{Q}\#\#$

(3) *Destressing counterfeeds GF:* raím+ét → raimét/*rajmét, "grape (dimin.)"

(4) *Destressing feeds GF across cyclic boundaries:* [nó[ínstár]] → nojnstár, "not to instate"

(5) *GF is blocked by SCC:* [[[ruín]óz]ísim] → ruinuzísim/*rujnuzísim, "very ruinous"

In (5), GF crucially fails to apply to the surface destressed vowel. This is due to the SCC: cyclic reapplication of the phonological grammar if there were no SCC ("fully cyclic reapplication") would predict [[[ruín]óz]ísim] $|_{cyc_1}$ → (D) [[ruinóz]ísim] $|_{cyc_2} \rightarrow^*$ (GF) [rujnózísim] → (D) [rujnozísim] (→ (Reduction) [rujnuzísim]). The SCC requires that a rule on cycle j be triggered by information uniquely available on cycle j, whether it be segmental material appearing only in cyclic domain j, or more deeply nested material altered by a previous rule of cycle j. In this case, the input to GF on cycle 2 is the sequence [ui], an illicit trigger because it is properly in the domain of cycle 0 and is generated (by D of [í]) on cycle 1.

It has been known since [5] that phonological grammars pick out only (a subset of the) regular relations—a robust and non-trivial generalization which contrasts sharply with syntax [8,9]—with the explicit caveat that naive reapplication at each cycle ("fully cyclic") would lead the system to exceed this restriction [5,7]. Given a phonological mapping R, (i.e., an entire grammar as would apply at one cycle), it is possible to define a derived grammar R_{cyc} which does not incorporate SCC or anything like it, reapplying R to the whole string at each level of nesting in an input morphosyntactic structure, i.e., $R_{cyc}([[[x][y]z]w]) = R_{cyc}([[R(x)R(y)z]w]) = R_{cyc}([R(R(x)R(y)z)w]) = R(R(R(x)R(y)z)w))$. It is easily shown that this relation is not regular, since, e.g., a single insertion could reapply at the same locus at each cycle so that the number of inserted elements would track the number of surrounding brackets, yielding a language reducible to the properly context-free language $a^n b^n$.

I show that the SCC can be formalized in a way that resolves this. I give here a summary of the reasoning. R_{dec} is a version of the grammar where all non-identity mappings are blocked (i.e., any changes to segments are changed to identity mappings) unless a bracket or a non-identity mapping is found in the environment. (The proof uses a representation of a grammar as a finite set of non-identity mappings as a mathematical convenience, but this by itself is orthogonal to whether derivational or constraint-based theory is the best psychological characterization of the computation: see [5,7,16,17]. I also restrict attention to the distribution of input–output alternations and not static phonotactic generalizations.) The regularity of $(R_{dec})_{cyc}$ is demonstrated by constructing a slightly modified R_{dec}, R_{ext}, adding, for each non-identity mapping, an ad-

ditional set of changes accounting for all of the finitely many possible cyclic interactions with other changes (segment $A \rightarrow B$ on cycle i, then $\rightarrow C$ on a later cycle by a change which is otherwise effectively counterfed). If not for such interactions, R_{dec} would be equivalent to $(R_{dec})_{cyc}$; since there are only finitely many possible cyclic interactions, each can be cast as a distinct (regular) change and incorporated into R_{ext}. This construction is repeated until there are no distinct environments to be added, yielding R_{ext}. Crucially, the restriction to derived environments guarantees that the number of distinct environments eventually goes to zero. In contrast, the construction would be insufficient to reconstruct R_{cyc} from R, where new distinct environments can be created by countercyclic application (e.g., insertion and re-insertion at the innermost cycle), creating unboundedly many cyclic interactions. The grammar so constructed from R_{dec} can be shown to be equivalent to $(R_{dec})_{cyc}$, however, demonstrating that the SCC serves to pull a phonological system interfacing with morphosyntax in an "inside-out" manner back within the biological limits of phonological processing, as the entire cyclic phonological grammar can be compiled into a single regular relation, R_{ext}. In short, cyclic opacity is argued to be a compromise between the non-regular nesting structure of the syntax and the limited computational capacity of the phonology. Although cyclic opacity fell out of focus in the phonological literature for some time, [3,18], the current result implies that cyclic opacity in phonology reveals a crucial part of the explanation for the architecture of grammar.

I also offer suggestions on how the SCC might be seen to be an "optimal" compromise. In particular, although for particular grammars other restrictions (or no restrictions) would offer closer approximations to R_{cyc}, I speculate that the SCC may be the best general strategy for regularization and provide a criterion that can be used to confirm or deny this conjecture in future research. Finally, I note that the explanation cannot in principle transfer directly to cyclic opacity effects in syntax, first, because cyclic opacity is a much stronger condition in syntax than in phonology, barring interactions beyond a certain distance rather than just requiring an intervening cyclic boundary, and, second, because syntactic computation is not regular in the first place. Nevertheless, the fact that island effects are in general restricted to overt movement [15] suggests that the two may yet be related.

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