**Constituent Structure and the Binding Problem**

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**Abstract**. Van der Velde & de Kamps' model encodes complex word-to-word relations in sentences, but does not encode the hierarchical constituent structure of sentences, a fundamental property of most accounts of sentence structure. We summarize what is at stake, and suggest two ways of incorporating constituency into the model.

We are impressed by van der Velde & de Kamps' attempt to take seriously the challenge of capturing the complexity of human language in a neurally plausible model. Their model makes it possible to ask questions about the encoding of the details of sentence structure that it was difficult to even ask previously. This is no mean achievement. Nevertheless, we are concerned that the authors' model avoids one of the most fundamental properties of sentence structure, and that this could seriously restrict the scope of the model.

Although many of the figures in the target article bear a superficial resemblance to the phrase structure trees of linguistics, the sentence structure representations in the neural model lack the hierarchical constituent structure encoded in phrase structure trees. Phrase structure trees encode bindings between primitive elements (words) that create constituents and also bindings between constituents that form larger constituents. In van der Velde & de Kamps' model, in contrast, only bindings between the basic word-level structural assemblies are encoded. A verb's theme sub-assembly may be temporarily bound to a noun's theme sub-assembly to form the equivalent of a simple verb phrase, but the verb phrase does not itself combine with other sub-assemblies to form larger constituents. The 'S' and 'C' structural assemblies that are employed in the encoding of main clauses and embedded clauses respectively do not delimit clause-sized constituents. Rather, they are word-level structural assemblies whose sub-assemblies bind with the sub-assemblies of other word-level units.

The binding of words and phrases to form hierarchically organized constituent structures is a property shared by a wide variety of linguistic models that differ in many other respects (e.g., Chomsky, 1965; Bresnan, 2001; Pollard & Sag, 1994; Steedman, 2000; Goldberg, 1995; Frank, 2002), and it plays a crucial role in explanations of many linguistic phenomena. These include the following:

(i) Coordination rules. In most cases, like categories can be combined with the conjunction *and* to form a larger instance of the same category: nouns coordinate with nouns, verbs with verbs, verb phrases with verb phrases, etc. In the absence of a mechanism for encoding recursive constituent structures in van der Velde & de Kamps' model, it is difficult to capture the fact that *John and Mary* is a noun phrase that governs plural verb agreement, or the fact that *The managers and the pilots who supported the strike* is a noun phrase in which the relative clause may modify only *pilots* or both *managers* and *pilots*.

(ii) Anaphoric relations. Languages make extensive use of anaphoric expressions that are interpreted as taking the meaning of another constituent in the sentence or discourse.

Pronouns such as *he* or *them* may corefer with another noun phrase constituent, and forms like *it* or *so* may be anaphoric to a clause-sized constituent, as in *The sun was shining, but Sue couldn't believe it*. The expression *do so* is anaphoric to a verb phrase, which may be a larger constituent, as in *Bill finished his homework on Tuesday and Sally did so too*, or a smaller constituent, as in *Bill finished his homework on Tuesday and Sally did so on Thursday*. It is difficult to capture such dependencies in a model that lacks hierarchically organized constituents.

(iii) Long-distance dependencies found in wh-questions, topicalization, relativization passivization, raising, and scrambling structures consistently involve the appearance of a constituent in a non-canonical position. It is difficult to capture such rules without constituents.

(iv) Scope relations. Recursive formation of constituents makes it straightforward to capture the fact that the expression *second-longest American river* refers not to the Amazon – the second longest river, and also an American river – but rather to the Mississippi-Missouri, which is the second longest among American rivers.

(v) Command relations. Many syntactic relations are restricted to constituents that stand in a *c-command* relation, the relation that holds between a constituent and its sister and all subparts of its sister. For example, negative polarity items such as *ever* and *any* must be c-commanded by a negative expression. This constraint captures the acceptability of *Nobody thinks that Bill ever sleeps* and the unacceptability of **A man that nobody likes thinks that Bill ever sleeps*. The absence of constituents in van der Velde & de Kamps' model makes it more difficult to capture structural generalizations of this kind.

(vi) Recursive modification. Modifier expressions such as adjectives and relative clauses may be freely combined with the categories that they modify, in any quantity, as in *six big red India rubber balls*. In grammars with hierarchically organized constituents this can be easily captured using a recursive rule such as *N'* → *Adj N'*. In van der Velde & de Kamps' model, however, modifier expressions are bound to the categories that they modify by means of dedicated sub-assemblies, and multiple modifiers require multiple dedicated sub-assemblies. It strikes us as inefficient to require all noun structural assemblies to include a special adjective sub-assembly that is exploited only in noun phrases with 6 or more adjectives.

Van der Velde and de Kamps correctly note that combinatorial productivity and recursive productivity are separable issues. Combinatorial productivity can obtain in the absence of recursive productivity, so long as there is arbitrary binding between fillers and roles. Recursive productivity, they note, "deals with the issue of processing more complex syntactic structures, such as (deeper) center-embeddings" (§4.2). The above discussion illustrates, we hope, that, at least for natural language, recursive productivity – i.e., constituent depth – is at issue even for simple syntactic structures.

We can imagine at least two ways in which the neural blackboard architecture could be extended to encode hierarchical constituent structure without sacrificing the main insights of the model. One possibility would be to add new structural assemblies that correspond to non-terminal nodes in a phrase structure tree. For example, assemblies for the categories NP and VP would bind with other categories and not with individual words. All NP assemblies would then need to have a number of sub-assemblies that would allow them to bind with any potential mother or daughter node of NP. An alternative possibility would be to directly exploit the delay assemblies that are activated in a memory circuit when a pair of sub-assemblies is bound together. If the delay assembly could double as a structural assembly for a constituent node that could bind with other constituent nodes, then this might allow encoding of hierarchical constituent structure. Indeed, van der Velde & de Kamps hint that a pair of bound structural subassemblies can themselves be bound to another pair of bound subassemblies, when they draw a dotted line between the 'n' and 'v' subassemblies in Figure 10 as a means of capturing subject-verb agreement. Crucially the model must be able to encode not only the first-order relationships between word-level primitives, but the second-order relationships between relationships that characterize constituency in natural language.

Whether these or any other solutions turn out to be most feasible, we suggest that the neural blackboard architecture cannot properly address the challenge of the 'massiveness of the binding problem' (Jackendoff, 2002) unless it is able to recursively encode constituents and bindings among constituents.

## References


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