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STRUCTURE MAPPING AND SEMANTIC INTEGRATION IN A CONSTRUCTION-BASED NEUROLINGUISTIC MODEL OF SENTENCE PROCESSING

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Abstract

The current research provides a theoretical, computational and neurophysiological framework in which particular aspects of sentence comprehension and non-linguistic sequence transformation processing are implemented by a common neural mechanism for structure mapping. The theoretical context is derived from construction grammar theory in which language is considered in terms of a structured inventory of form to meaning mappings. Computationally, the construction grammar concept is implemented in a hybrid neural network model that is derived from functional neuroanatomical studies. In particular, based on data from Hoen et al. (2006, this issue), the generalized structure mapping capability is attributed to a local cortical network that includes Brodmann's area (BA) 44, while the integration of semantic structure into this transformation mechanism relies on BA 45.

Key words: construction grammar, basal ganglia, cortico-striatal system, simulation

Introduction

The current paper attempts to reconcile functional aspects of language processing with the underlying neural architecture of Broca's area and the ventral premotor cortex that provides these functions. We will first provide a functional characterization of language comprehension in the context of the construction grammar framework (Goldberg, 1995; Tomasello, 2003). We will then outline the implementation of this functionality in a computational architecture that relies on well-characterized neuro-computational functions including working memory, associative memory and recurrent networks that are put together in a novel architectural manner. We finally establish the correspondence between the functional components of this architecture (structure mapping and semantic integration), and brain regions (Brodmann's areas 44 and 45 respectively – BA 44, BA 45) in a manner that can be directly tested via psycholinguistic and brain imagery experiments. The results of the most recent of these tests are reported in Hoen et al. (2006, this issue).

Functional Characterization of Language

Language is a function that allows us to map sentences onto meanings, in comprehension, and meanings onto sentences in production. These mappings define the relations between words in sentences, and aspects of phrasal semantics including thematic role assignment, time, mode and aspect. In the current analysis we concentrate on thematic role assignment, though this analysis generalizes to other aspects of phrasal semantics.

In the construction grammar framework, these sentence-form to meaning mappings are stored in a structured inventory, and define the syntactic processing capability of the language system. Constructions can be fixed, holistic objects like "Kick the bucket" or "Gimme that", or they can be more abstract as "Gimme X...". To give a concrete example, consider the three sentences:

1. John gave Mary the ball.
2. John gave the ball to Mary.
3. The ball was given to Mary by John.

Barring pragmatic aspects of focus, these three sentences all correspond to the meaning: gave (John, ball, Mary), coded in an EVENT (AGENT, OBJECT, RECIPIENT) format. In the construction grammar formalism, each of these three sentence types maps onto the meaning in a different manner (Goldberg, 1995). The three distinct mappings between sentence-type and meaning correspond to three distinct grammatical constructions, each of which can generalize to an open set of sentences of the corresponding construction type.

Because of the many degrees of freedom in this mapping, both within languages (e.g., active and passive voices) and across languages (e.g., different canonical word order, differences in word order flexibility), the language system must be flexible in its ability to acquire these form to meaning mappings. Bates et al. (1982) proposed that across languages, a finite set of cues are used, in varying language-specific distributions, that allow the encoding of phrasal semantics. These cues include word order, grammatical marking, lexical categories and prosody. The two principal lexical categories are those of the open class (or content) words including nouns, verbs, adjectives on the one hand, and closed class (or function) words including prepositions, determiners and auxiliary verbs on the other.

Now, considering sentences such as:

4. The ball that John threw broke the window.

5. The window was broken by the ball that John threw.

Both correspond to the meaning expressed by a linked pair of events:

THROW (JOHN, BALL)

BREAK (BALL, WINDOW)

The construction grammar framework (Goldberg, 1995; Tomasello, 2003) provides grammatical constructions that account for these complex sentences as well (simulated in Dominey, 2003). These abstract constructions are generative in that the open class words (i.e., nouns, verbs, etc.) can be replaced with other open class words of the appropriate category. However, as presented here, the system is not compositional (i.e., it must learn new grammatical constructions rather than generating them autonomously), though this can be addressed. Briefly considering relative clauses in sentences 4 and 5, statistical pattern finding mechanisms can determine the local structure of noun phrases such that these can become units that can be inserted as nouns into existing constructions, thus yielding a flexible compositionality capability (see Tomasello, 2003).

Clearly this characterization is at odds with generative approaches that employ a hidden layer of syntactic structure between sentence types and meaning (e.g., Chomsky, 1995). For the current purposes, however, both camps agree that the set of cues proposed by Bates et al. (1982) play an important role for the sentence processor to establish the mapping from sentence to meaning.

Implementation in a NeuroComputational Model

Given this functional characterization of sentence processing, we now present a neuro-computational model that can perform this processing, illustrated in Figure 1. In 1A, as the sentence is processed word by word, open and closed class words are segregated into distinct processing streams. This is not unrealistic, as newborns can perform this categorization (Shi et al., 1999), and several neural network studies have demonstrated lexical categorization of this type based on prosodic cues (Shi et al., 1999; Blanc et al., 2003). Open class words are then translated into their referent meanings. The next crucial step is the mapping of these referent meanings onto the

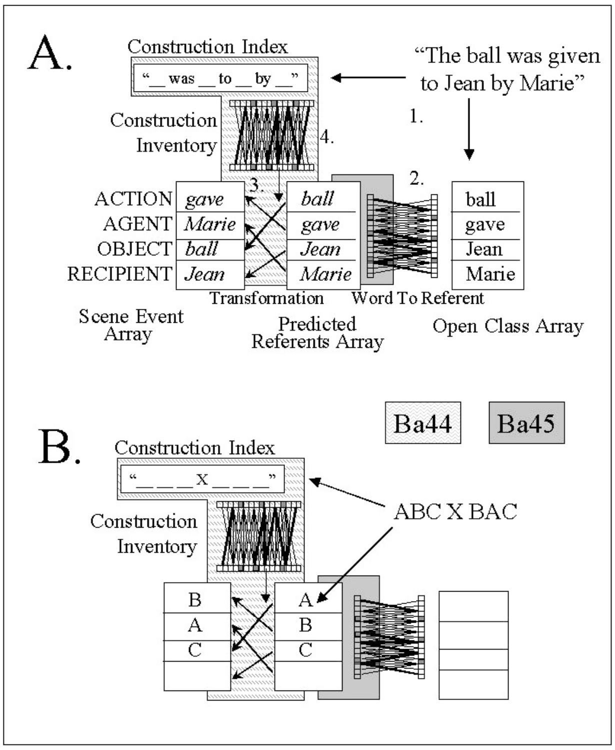

Fig. 1 – *Structure-Mapping Architecture. A. Sentence Comprehension: 1. Lexical categorization – Open and closed class words processed in seperate streams. 2. Open class words in Open Class Array are translated into their referent meanings via the Word To Referent mapping. Insertion of this referent semantic content into the Predicted Referents Array (PRA) is realized in pars triangularis Ba 45. 3. PRA elements are mapped onto their roles in the Scene Event Array by the Transformation mapping, specific to each sentence type. 4. This mapping is retrieved from Construction Inventory, via the Construction Index that encodes the closed class words that characterize each grammatical construction type. The structure mapping process is associated with activation of pars opercularis Ba 44. B. Abstract Sequence Processing: Lexical categorization takes place for function and content elements of non-linguistic sequences (see Hoen and Dominey, 2000). As with sentences, function elements allow retrieval of learned transformation from Construction Inventory via Construction Index.*

appropriate components of the meaning structure. In Figure 1A, this corresponds to the Transformation from the Predicted Referents Array onto the Scene Event Array. This mapping varies depending on the construction type (as in sentences 1-5 above). Thus, the system must be able to store and retrieve different sentence-to-meaning Transformations appropriate for different sentence types. This is where the closed class words (the ensemble of Bates et al., 1982, cues in the general case) are used. The closed class words, and their relative positioning within the sentence are represented in the Construction Index. The requirement is that every different grammatical construction type should yield a unique Construction Index. This construction index can then be used in an associative memory to store and retrieve the correct sentence-to-meaning Transformation. Note that the numbered steps (1-4) in Figure 1 are for functional clarity, and do not reflect a serial processing order. Rather, the temporal evolution of these processes in the model is consistent with a three phase system with a first phase of lexical categorization, a second phase of lexical semantics and argument structure (Transformation) retrieval, and a final phase of structural mapping (see Friederici, 2002).

The model in Figure 1 has been implemented as a hybrid neural network that employs associative memory and working memory functions. The model has been demonstrated to learn a variety of grammatical constructions including active and passive forms with two and three arguments, and relative clauses as in sentences 4 and 5 above (Dominey, 2003). We have also demonstrated that the model extends without modification to Japanese (Dominey and Inui, 2004), thus providing additional cross-linguistic validation of the underlying theory.

This model led us to propose a series of "audacious" (Nespoulous, personal communication) predictions and experiments based on the idea that the structure mapping mechanism could be directly accessed, independent of language, as illustrated in Figure 1B, where the semantic integration function of BA 45 is bypassed. We thus demonstrated that agrammatic aphasics had correlated impairments in syntactic comprehension and "grammaticality" judgement tasks with abstract non-linguistic letter sequences (Lelekov et al., 2000b; Dominey et al., 2003) similar to that in 1B. To further establish the functional link underlying this correlation, we demonstrated that training on abstract sequences transferred to improved performance on analogous sentence comprehension (Hoen et al., 2003). Several ERP studies established neurophysiological correlates between processing of abstract sequence structure and grammatical structure (Lelekov et al., 2000a; Hoen and Dominey, 2000). In particular, we performed ERP experiments in which the non-linguistic equivalents of function words were used in abstract sequences. As predicted by the model, we observed an LAN effect for transformation-related function symbols in non-linguistic sequences (Hoen and Dominey, 2000). Perhaps most conclusively, Hoen et al. (2006, this issue) report new data from an fMRI study that directly compares sentence and abstract sequence processing that confirms this theoretical model, and begins to identify the underlying neural substrates.

Correspondence with Brain Architecture

The structural transformation processing that involves the Construction Index and selection of the appropriate Transformation mapping relies on a non-language-specific transformation processing mechanism that corresponds to a local cortical network including BA 44, 46, 9 and 6. Primate neuroanatomy and human brain imagery indicate that at least part of this network, in particular area 46, corresponds to the frontal component of the dorsal visual stream (Ungerleider et al., 1998), consistent with its proposed role here in structural transformation processing. We have suggested that this mechanism relies on recurrent cortical networks and corticostriatal processing (Dominey et al., 2003) consistent with and extending the procedural component of Ullman's (2004) sentence processing model. The ConstructionIndex reflects the cortical integration of closed class elements that, via corticostriatal circuitry, retrieve the appropriate Transformation implemented in this frontal transformation processing network that includes BA 44.

In contrast, for sentence comprehension the integration of lexico-semantic content into Predicted Referents Array for subsequent Transformation processing corresponds to a ventral stream mechanism that culminates in the pars triangularis (BA 45) in the inferior frontal gyrus region (Ungerleider et al., 1998), consistent with the declarative component of Ullman's model (2004). Interestingly, though this area (BA 45) was specifically activated in the language task in our experiment (Hoen et al., 2006, this issue), it is more generally characterized as participating in object or semantic (*vs.* spatial) working memory functions (reviewed in Ungerleider et al., 1998), consistent with its proposed role here for semantic integration.

Conclusion

The results of this study and the accompanying research report (Hoen et al., 2006, this issue) support the emerging view that from a language processing perspective, the pars opercularis (BA 44) is involved in the structural processing of syntax, while the pars triangularis (BA 45) is involved in the integration of semantics into this structure (Newman et al., 2003). This is consistent with models of dissociated processing of structural rules and lexical semantics (Dominey, 1997; Ullman, 2004; Chang, 2002). Our novel and innovative finding here is the integration of this ensemble of results into a theoretical and neuro-computational construction grammar framework that accounts for the linguistic and non-linguistic structural transformation processing in BA 44 of Broca's area.

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