A cognitive model of incremental structure-building during language processing using an LFG-based representation

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This paper presents a cross-linguistic (Korean/English) computational model of structure-building during language processing, constructed in the ACT-R computational cognitive environment (Anderson, 2007), which is a first step in modelling the relationship between structural and inferential computation in language processing.

Grammar and Processing Psycholinguistic theories such as Good Enough Processing (Ferreira et al., 2002), the Cognitive Equilibrium Hypothesis (Karimi and Ferreira, 2015) and Processing Competition (Kos et al., 2010) propose that inferential processing of language content takes place simultaneously with structural parsing. However, the nature and role of grammar theories in accounts of structural parsing are often poorly-defined, and thus the relationship between a developing syntactic structure and a composed (as opposed to inferred) semantic representation is opaque. LFG analyses are available for language fragments as well as complete utterances, and generate a transparent relationship between form and meaning. Accordingly, an incremental processing model based on LFG may offer a more precise way of modelling interactions between structural and inferential cognition. While LFG's modular separation of universal (f-structure) and language-specific (c-structure) representations is attractive for cross-linguistic modelling, this dual representation of syntax presents challenges for models of cognition.

Modelling Cognition Computational cognitive models of language processing have been used for at least twenty years (e.g. Lewis, 1999). ACT-R is a symbolic architecture that models cognition using a restricted set of buffers to represent working memory. These buffers create, retrieve, and carry out processing operations on symbolic chunks of declarative memory, governed by a set of production rules held as procedural memory. Retrieval of memory chunks into the buffers is cue-based, with chunk activation (a sub-symbolic property of individual chunks) determining which chunk is selected when a choice is possible. A production is selected by matching the contents of working memory buffers to its conditions for firing. Here too, the sub-symbolic property of production utility determines which production is selected where a choice is possible. The pre-eminent ACT-R language structural processing model (Lewis and Vasishth, 2005) generates outcomes that match experimental time-courses of complex English sentence processing. To achieve this, however, it assumes significant extra buffer capacity, is not based on an explicit theory of grammar, and uses a language-specific production set.

LFG Syntax in ACT-R Deriving f-structure from c-structure requires the ϕ projection function to be computed, which in turn requires productions to fire. ACT-R's assumption of a 50ms cycle for production firing has been supported in many cognitive contexts. Accordingly, sequential generation of f-structure after c-structure adds processing time to the model, which reduces the likelihood of the model's output matching experimental data. It is possible to write productions that generate c-structure and f-structure simultaneously, but this conflates language-specific and universal calculations and thus restricts the model to a single language. The model presented here takes a third route, using a cross-linguistic single production set to generate a structural representation termed an *F-representation* that combines elements of c- and f-structure, using lexically-specified ordering and category combination constraints.

The F-representation Formally, the F-representation is a function whose domain is a partially ordered set of attributes that are taken or derived from c- and f-structure, and whose range is a set of values that may be atoms, F-representations, or sets of atoms or F-representations. Table 1 lists F-representation attributes and their derivation. In the definitions, F is the F-representation corresponding to f-structure f where the two have identical PRED values. Following Dalrymple (2017), category values are taken to be a feature set.

Table 1: Relationship of F-representation attributes to c- and f-structure

Derived from c-structure	
CAT	Category of word providing the PRED value
MA.CAT	The category of the word supplying the PRED value for the immediately-containing f-representation. This can be specified as a constraint in the lexical entry providing the PRED value. The formal definition of the attribute uses the λ labelling function and M mother function over c-structure nodes, together with ϕ^{-1}, the inverse of the c- to f-structure projection function: $F\ \mathrm{MA.CAT} = \lambda(\mathrm{M}(\bullet_x)) : \bullet_x \in \phi^{-1}(f) \wedge (\mathrm{M}(\bullet_x)) \notin \phi^{-1}(f)$
GF ordering constraints	Lexically specified. Formally, $f\ \mathrm{GF}_1 \prec_f f\ \mathrm{GF}_2 \Rightarrow F\ \mathrm{GF}_1 \prec F\ \mathrm{GF}_2$
Derived from f-structure	
PRED	Required in all F-representations
Governed GFs	Specified by the lexical entry providing the PRED value
ADJ	Available if specified in the lexical entry providing the PRED value
FEATURES	Available if specified in the lexical entry providing the PRED value

The Model Two types of declarative memory chunk are used: lexical specifications, and structural chunks which correspond to F-representations. Procedurally, the model uses a single set of ACT-R productions to parse both English and Korean, with language-specific constraints introduced through the lexicon. Creating and manipulating the structural chunks requires an increase in the cognitive capacity of ACT-R, but the four additional buffers are fewer than the 12 buffers added by Lewis and Vasishth (2005).

The scope of the model is a subset of the overall language grammar, that covers relevant psycholinguistic experimental stimuli. For Korean, the model uses the type-based phrase-structure rules proposed by Cho and Sells (1995) to generate the lexical specifications. The corresponding specifications for English are derived from Falk (2001). Attachment of a chunk as a dependant requires a head to be identified, and a grammatical function to be assigned to the dependant. The model's output is a sentence structure, presented as a directed graph; the model time-course assumes that a word must be attached before the next word in the sentence can be attended.

Results Results are presented in Figures 1 and 2 for the outputs of the model when processing the English and Korean versions of sentence (1) adapted from Kwon et al. (2010).

(1) *yumyenghan sayngakkaka chwukceney chotayhan cihwuycaka uywonul*
famous vocalist.SBJ festival.OBL invited conductor.SBJ senator.OBJ
moyokhayssta
insulted
"The conductor who the famous vocalist invited to the festival insulted the senator."

Figure 1 shows the structure generated by the model when parsing the sentence input in the two languages. The structures are essentially similar: differences include the presence of prepositions and relative pronouns in English, and the chunk reference numbers reflect the different order of chunk creation. Figure 2 compares the time-course generated by the model (red) compared to experimental eye-tracking data from Kwon et al. including first-pass (blue) and regression path (green) times.

The structural outputs provide evidence that the model is capable of parsing embedded sentences. Time-course data for Korean are in line with first-pass eye tracking times. However, empirical regression path times are considerably longer. This may reflect the model building structure too quickly, or increased processing load for human subjects undertaking tasks other than initial structure-building.

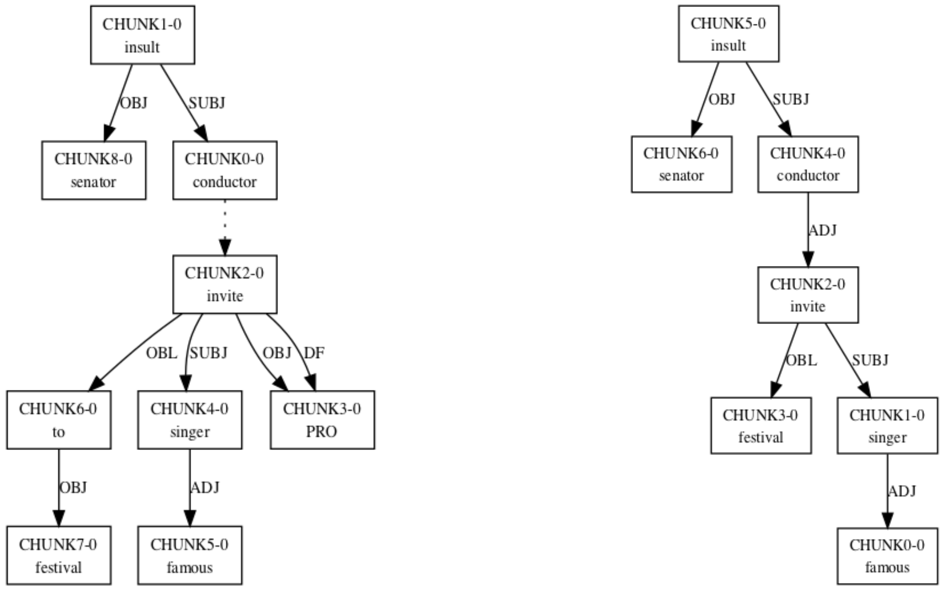

Figure 1: Output for English (left) and Korean

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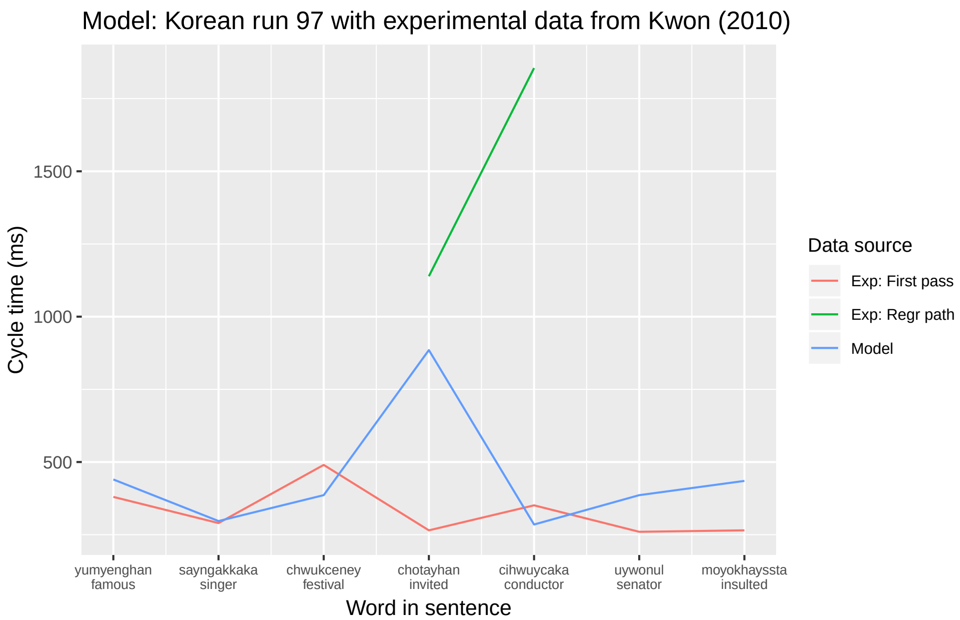

Figure 2: Model and experimental time-course