Issues in Implementing Three-Level Semantics with ACT-R

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Abstract

Three-level semantics is a cognitive theory of how readers construct meaning from text. It incorporates concepts like conceptual schemata and activation spreading that are suited to implementation on a cognitive architecture. After summarizing the structure of the theory, we point out critical aspects of its implementation with ACT-R that are, besides the adaptation of the theory, expected in gathering empirically valid cognitive representations and activation values.

Keywords: text understanding; cognitive linguistics; ACT-R; representation; base-levels; spreading activation

Three-Level Semantics

Given that even computational linguists reconsider the reader's impact on meaning (Hirst, 2008), it is time for cognitive linguists to model their reader-oriented theories computationally. We therefore briefly sketch three-level semantics (Schwarz, 1992) that constructs current meaning from concepts and a mental lexicon, before pointing out issues in implementing it with ACT-R (Anderson et al., 2004).

Conceptual Schemata

In three-level semantics, *conceptual schemata* from long-term memory represent amodal information. Three-level semantics uses the definition of Bierwisch (1983), who posits that a concept is "determined by a schema $[t,[a_1,...,a_n]]$, where t is a conceptual type, and $[a_1,...,a_n]$ is a system of explanatory principles according to which concepts develop." Bierwisch exemplifies conceptual types with individuals, kinds, properties, relations and events. The explanatory principles or conceptual primitives stem from Moravcsik (1981) and describe substance, structure, function and causal relations. Schemata for different readers are structured using different primitives, as can be seen from the classical example of the WATER concept: children will not know that water is the substance H_2O, but rather that it is a liquid that can be drunk or be used to quench a fire. Each of these primitives has an individual activation value. When using three-level semantics, e.g. in Schwarz-Friesel (2007), scripts are frequently used, that could be represented using conceptual primitives.

Mental Lexicon

Language-specific knowledge is organized in a mental lexicon that assigns phonetic and graphemic information to sets of amodal conceptual primitives. By definition, a lexicon entry of a concept does not comprise all its primitives, but only those that are necessary parts or features of the concept, irregardless of context. In the case of the concept WATER, a lexicon entry can contain the information that it is a liquid substance also called H_2O. Lexicon entries also provide syntactic information and may relate to a concept family, e.g. the word *bath* can mean a bathtub, a bathroom, the act of bathing, etc. Distinguishing concepts and lexicon entries also allows one to model concepts that a subject cannot verbalize directly, but only through paraphrase, e.g. using *star-shaped screw head* instead of *Torx head*.

Current Meanings

The third level explains the construction of language- and context-specific current meaning from context-invariant lexicon entries. Two processes play a major role here: selection and specification. Because meaning is to be represented in capacity-limited short-term memory, only a small number of a lexicon entry's representations can be selected. Additionally, the selected graphemic and phonetic representations become conscious. Since each primitive has an individual activation value, selection of representations is determined by context-specific activation. Besides selection, context can induce a specification, as in *He loved his car, no matter how old it was – it's been the first one in his shadow box*, where the prototypical current meaning of an old car gets replaced by a prototype of a toy car. Besides context effects, the distinction between lexicon entries and current meaning can also model tip-of-the-tongue phenomena as delayed availability of the phonetic representation after conceptual primitives have already been activated.

Implementation Issues

While three-level semantics has already been applied in studies of context-specific meaning construction like Schwarz-Friesel (2007), it has not been implemented computationally so far. Some implementation choices in ACT-R are quite natural, though: processes and strategies used in three-level semantics can be implemented using productions and context may be modeled as slots of chunks in ACT-R's goal buffer. Lexical and conceptual knowledge as well as spreading activation are implemented in the declarative module.

Conceptual Schemata

Conceptual schemata can be modeled in ACT-R as chunks with a slot providing their conceptual type as well as further slots for the primitives that model features of the concept and relations it is involved in. Modeling features and relations as individual chunks allows them be activated individually, as required by the theory. Schemata might be hand-coded which is slow and leaves the empirical validity to the developer or a pre-study. Also, a consistent and powerful set of conceptual types and primitives would need to be developed. Alternatively, projects like Cyc could provide a set of conceptual types and primitives as well as the contents of lots of schemata, but might lack application-specific knowledge (Ball, Rodgers, & Gluck, 2004).

Mental Lexicon

Entries in the mental lexicon will be modeled using different types of chunks depending on the part of speech of the word they represent. Lexicon entries provide slots for syntactic information as well as chunks modeling conceptual primitives, graphemic and phonetic representations. Since not each form of a word is to be represented in a lexicon entry, morphological processes need to be implemented, too. Similar to schemata, entries of the mental lexicon do not need to be written by hand but can be derived from lexical databases like WordNet (Emond, 2006) and FrameNet.

Current Meanings

Current meaning can be implemented using a chunk type that has slots for the conceptual primitives and graphemic and phonetic information that is supposed to be conscious. While activation-based selection needs a proper implementation of context, specification requires the availability of suitable prototypes. How to construct them is still to be clarified.

Activation

While a configurable spreading activation algorithm is given by ACT-R, initial base-level (i.e. long-term) activation values are needed. Base-levels for lexicon entries could be derived from word frequencies provided by corpora, as proposed by Emond (2006). Base-levels for conceptual primitives, schemata, graphemic, phonetic and syntactic representations are not as readily available and cannot be hoped to be derived from word frequency data. Learning by reading as mentioned by Hirst (2008) might help here by incorporating activation spreading caused by cognitive processing during reading. Due to the three levels and the fine-grained chunks at these levels, multi-level spreading activation is needed to avoid redundant representations (Ball, 2012) and to be able to select contextually relevant parts of representations. To ease understanding of activation dynamics, a tool for plotting time series of modeled activation values would be helpful, e.g. to show why certain conceptual primitives become part of current meaning while others do not. Such a tool might also be helpful in teaching three-level semantics.

Memory

Three-level semantics is based on four kinds of memory: sensory, short-term (STM), working (WM) and long-term memory (LTM). Schwarz assumes that stimuli take about 250ms before they can pass from sensory memory to consciousness and that they are subject to interaction with LTM. Sensory memory can be implemented via ACT-R's aural-location and visual-location buffers that can spread activation to LTM. Top-down processes using information from LTM to modify perception would need to be implemented as productions. Schwarz assumes that only mode-specific (e.g. verbal or visual) information can become conscious in STM. Conscious STM may be implemented using ACT-R's imaginal buffer. WM and LTM are implemented as levels of chunk activation in the declarative module of ACT-R.

Conclusions

A computational implementation of three-level semantics with ACT-R will serve to further determine the theory and test it against short texts of limited grammatical complexity. The implementation will require finding and integrating suitable knowledge representations, generating base-levels and implementing multi-level activation spreading before one can verify the model by reproducing empirical data. Such verification will be iterative: e.g. reproducing significant differences in reference resolution will require, but not suffer from, an unverified implementation of lexical access. The verified parts of the model are important to tell efficiently whether three-level semantics can explain empirical data.

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