ACT-R: a higher-level account of processing capacity

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Abstract:

We present an account of processing capacity in the ACT-R theory. At the symbolic level, the number of chunks in the current goal provides a measure of relational complexity. At the subsymbolic level, limits on spreading activation, measured by the attentional parameter W, provide a theory of processing capacity, which has been applied to performance, learning and individual differences data.

Commentary:

In their target article, Halford, Wilson, & Phillips (HW&P) propose that cognitive limitations on information processing capacity should be defined in terms of relational complexity. They argue that limits on activation, as introduced in (Anderson, Reder, & Lebiere, 1996), do not provide a general metric for processing complexity. In this commentary, we argue otherwise by reviewing the ACT-R theory of processing capacity and examining how it relates to the relational complexity theory of HW&P.

A central concept in the ACT-R production system (Anderson, 1993; Anderson & Lebiere, in press) is that of the current goal, which represents the focus of attention. At each cycle, a production must first match the state of the current goal before performing memory retrievals and modifying the goal state. When a goal is successfully achieved, that goal chunk[1] becomes a declarative memory fact. Chunks are composed of a number of labeled slots, each of which holds a value which can be another chunk. Each chunk is an instance of a particular chunk type, which defines the name and number of slots. The mapping to relational knowledge is therefore fairly straightforward. Chunk types correspond to relations, with slots as arguments. Chunks correspond to relational instances, with slot values as fillers. The dimensionality of a relation equals the number of slots in the corresponding chunk type. Operations on relations, from basic omni-directional access to more complex ones such as analogy, are implemented in the manipulation of chunks by productions. The mechanisms to reduce the dimensionality of relations, chunking and segmentation, can also be used to reduce the size of goals. A new chunk (e.g. cat) can be defined as the combination of several slot values (e.g. c, a, t), then used as a single slot value in other chunks. Segmentation consists in performing a complex goal by pushing several smaller subgoals on the goal stack. The quaternary limit on relational dimensionality is generally compatible with the goal size in published ACT-R models.

We just sketched the correspondence between ACT-R and the relational account at the symbolic level. Some properties of relations, such as strength and asymmetry of access, result from subsymbolic activation computations in ACT-R, which control the retrieval of declarative chunks by productions. It is those

[1] This meaning of chunk is somewhat different from the meaning in (Miller, 1956).

activation computations that provide ACT-R's account of processing complexity. The activation of a chunk, which controls its availability, is the sum of a base-level activation, reflecting its past frequency of use, and an associative activation, reflecting its relevance to the current goal. Associative activation spreads from the current goal to declarative chunks. The associative activation of a chunk is the sum for each activation source of its source activation times the strength of association between the source and the chunk. The activation sources are defined as the slot values of the current goal, and a fixed amount of source activation W (1 by default) is divided evenly among the sources. Therefore, as the goal becomes larger, W will be divided among more sources and the resulting activation will be spread among more chunks, diluting the effect of the focus. As established first in (Anderson, Reder, & Lebiere, 1996) and more generally in (Anderson & Lebiere, in press), this dilution of activation will result in poorer performance, i.e. longer latencies and more frequent errors. In addition to impacting performance, large goal sizes also hinder learning. Lebiere (in preparation) establishes that a set of related chunks can only be reliably learned if the source activation for each chunk component is higher than the activation noise level. Therefore, given a particular noise level, simple facts (e.g. counting) might be learned but more complex facts (e.g. addition) might not because their components have lower source activation. This suggests that the gradual increase in processing capacity reported in the developmental data described by HW&P could be accounted for by a continuous increase in W. Finally, Lovett, Reder, & Lebiere (1997; in press) relate W to individual differences. They fit a range of subject performance on working memory tasks using a single ACT-R model, with high-performance subjects modeled by larger

W and low-performance subjects modeled by smaller W. All those results point to W as the basic measure of processing capacity in ACT-R.

ACT-R is not unrelated to the neural network models presented by HW&P. Lebiere & Anderson (1993) presented ACT-RN, a neural network implementation of ACT-R which uses essentially a positional encoding of symbol-argument-argument bindings, with clean-up memories as in convolution models. But we are not committed to any specific connectionist representation since, as HW&P report, they have the same basic properties. Just as theoretical computer science proved the equivalence of various computational paradigms in order to establish proofs of complexity valid for all, ACT-R aims to provide a higher-level definition of processing capacity independent of any lower-level neural representation.

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