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The Role of Sequential Dependence in Creative Semantic Search

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How do we search through our vast stores of knowledge to retrieve information demanded by the context and task at hand? Davelaar (this issue) finds that the words people report while searching for one word that is meaningfully associated with three cues (e.g., cues: comb, moon, dew; answer: honey; the Remote Associates Test, RAT) seem to be drawn from a superadditive combination of the semantic associations of the three cues, rather than "clustered" in pre-existing patches as expected by previous theories of semantic search (e.g., Troyer, Moscovitch, & Winocur, 1997). Although we found similar behavior in the same paradigm (Smith, Huber, & Vul, 2013), our interpretation hinged on a different property of search: There is sequential dependence between words reported during the search process. We believe that this sequential dependence is a fundamental feature of semantic search that gives rise to apparent clustering in previous work as well as providing further insights into Davelaar's current results.

When people list words that come to mind while solving RAT problems, responses that are closer in the sequence are more similar to one another than would be expected based solely on independent word selection, given the cue constraints (Smith et al., 2013). This holds both for words from the same semantic patch and those in different patches, indicating that semantic search is not simply sampling from sets of words or patches constrained by the cues, but that instead, the current state of the search process influences what will be retrieved next.

This sequential dependence has recently provided new explanations of behavioral phenomena in semantic search with a single cue. For instance, it has been well established that in the process of free recall—producing as many words as possible that relate to a given category—peoples' responses "cluster" (e.g., when listing animals, they might list several farm animals then some aquatic animals, etc.; Bousfield, 1953; Bousfield &

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Sedgewick, 1944; Gruenewald & Lockhead, 1980). This finding has been interpreted as evidence that free recall operates by a two-stage process: first searching for subcategories (e.g., farm animals or aquatic animals), then listing stored words from within those subcategories (Troyer et al., 1997; Wixted & Roher, 1994), which would suggest that memory is organized in categorical clusters.

However, more recent work suggests that semantic search is not a two-stage search-then-list process. Instead, responses tend to be related to prior responses, with occasional "resets" in the search process to start the search process de novo (Hills, Jones, & Todd, 2012). If semantic distance to the previous response influences which word will be chosen, then words will appear to cluster simply because after saying "cow" one is more likely to say "goat" than "shark." Breaks in the clusters could arise either because (a) responses after a reset are less likely to be related to prior responses, or (b) because responses that are only partially related to prior responses may cross category boundaries. Indeed, two models of semantic search that randomly walk through semantic networks without explicit clusters (though with resets) demonstrate the same clustering behavior as people (Abbott, Austerweil, & Griffiths, in press; Hills et al., 2012). These findings suggest that clustering may be an epiphenomenal consequence of the sequential dependence of human semantic search combined with the distribution of semantic relations among words rather than an organizing principle of the search process.

Considering this same sequential dependence in creative search tasks like the RAT potentially yields a different interpretation of Davelaar's results. Like Davelaar (this issue), we (Smith et al., 2013) found that responses are likely to switch at near-chance levels between "patches" of words defined by the semantic associates of the individual cues. On top of this, Davelaar finds that the cues combine in a superadditive fashion, since the probability of producing a word in response to all three RAT cues is greater than an additive combination of producing that word in response to the three cues individually. But if existing sequential dependence is not considered, responses may appear to be more grouped around the cues, when in fact this additional grouping is driven by the constraint of the prior response. For instance, if the cue constraints are actually additive, then when different cues produce adjacent responses, the second response may be more similar to the original cue solely because the first response is related to the original cue, and the second response is related to the first response; this may make the effect of the cues look superadditive (see Fig. 1). While it is possible that these response chains are based on both cue superadditivity and sequential dependence, only by considering that sequential dependence can the effect of the cues on the search process be fully determined. In addition, a model based on Hills et al. (2012) and Abbott et al. (2015) that considers an additive influence of the cues and sequential dependence emulates many of the diagnostic features of human RAT search behavior (Bourgin, Abbott, Griffiths, Smith, & Vul, 2014), suggesting that the sequential dependence might be a core component of the creative search process.

Our ability to quickly search through our vast stores of knowledge is a powerful capability of the brain, and investigating that search process is a key part of understanding

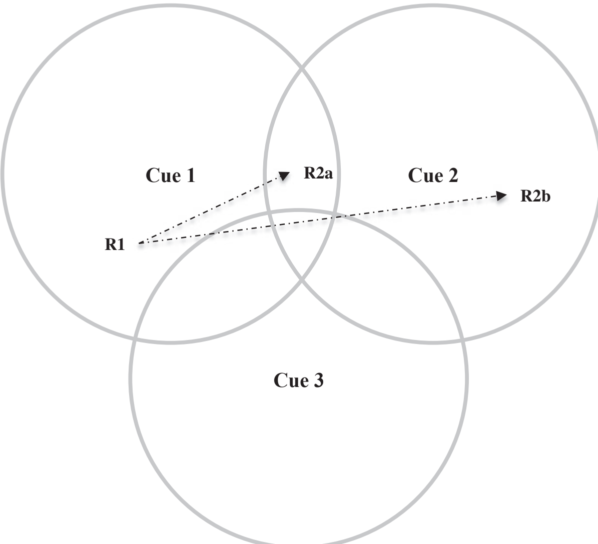

Fig. 1. Illustration of how even if cue influences are independent and additive, response chains may look superadditive if sequential dependence is not considered. In an additive system, two potential responses (R2a and R2b) are equally likely solely given Cue 2. However, if the first response (R1) influences the next response, R2a is more likely to follow. It, therefore, looks like Cue 1 influences the second response as well, but only by nature of the relationship of Cue 1 to R1.

how that knowledge is stored and accessed. Sequential dependence is a key component of this process that may be crucial to understanding how other features of search arise.

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