Connecting theory and practice on cognitive control via a joint embedding space of the scientific literature

Traditionally, theory and practice of Cognitive Control are linked via literature reviews by individual humans. This approach however, is biased by personal views, inadequate to track the ever-growing literature and yields redundancies and confusion [1]. A major source of confusion is *construct hypernomy* which occurs when the same idea is described differently in different contexts even though the same observable measures are used. For example, Cognitive Control, Executive Functions, Attentional Control, and Self-regulation are all constructs that may be "measured" using the same tasks; yet, these constructs are not widely considered equivalent. Our strategy to gain clarity on the relationships between tasks and constructs involves automated text analyses on an unbiased large body of scientific texts to create a joint representation of constructs and tasks. More specifically, 531,748 scientific abstracts are first mapped into an embedding space using a transformers-based language model that faithfully preserves the contextual information of the document; contrary to traditional methods such as bag-of-words. Document embeddings are then used to identify overlapping communities within a heterogenous graph of tasks and constructs, where community hypergraphs represent interconnected tasks and constructs. This joint graph embedding grounds constructs *on* tasks and allows for nuanced meaning of the constructs by taking advantage of constrained random walks in the graph [2]. We show that construct hypernomy in the literature can be reduced by regrounding constructs on tasks and refactoring them by overlapping communities rather than disjoint modules. We believe pulling theoretical and experimental literature into overlapping communities may greatly benefit researchers: the joint embeddings can be queried for task batteries, it may reveal knowledge gaps, and inspire the design of new tasks and novel hypotheses about the decomposition of cognitive functions. It may also be used in future applications to enhance literature searches.

Additional Detail. Rather than a dictionary definition of constructs, which may lack consensus, we propose a graph-based representation of the literature that regrounds constructs on tasks and redefines them as graph communities. By relaxing the modularity hypothesis (i.e., assumptions of independent, disjoint components), we show that overlapping and interconnected community hypergraphs drive a more fundamental model of constructs grounded on a set of tasks in a joint topic space.

Method. Using previous literature reviews [3-5], we first create a null heterogeneous graph where nodes are labeled with either task or construct names. We then collect a total of 531,748 published abstracts from PubMed (for 100 tasks and 72 constructs). Documents are then vectorized using a pre-trained Universal Sentence Encoder (USEv4) which was chosen for its high correlation with human judgment in sentence similarity benchmarks. Following recent approaches to topic modeling [5], the document vectors are then reduced in dimension and clustered to map them to a shared topic embedding space where documents are positioned with respect to their underlying topics. Document vectors in the topic space are then pooled together at every node of the graph, creating a single topic vector for each node. To predict links between nodes, we compute cosine similarity between all pairs. In order to populate only relevant paths between task nodes and construct nodes, we applied metapath2vec [2] to the affinity matrix. Finally, we apply spectral clustering to the affinity matrix to identify communities of nodes with spectral gap as a heuristic for the number of clusters.

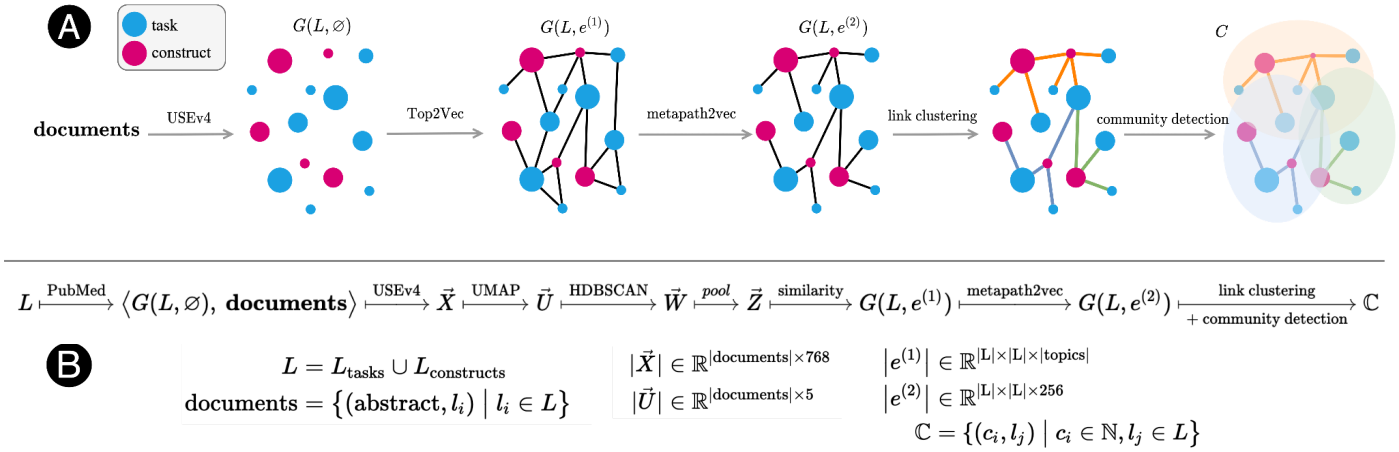

Figure 1. (A) Graphical and (B) computational views of the analysis pipeline; L: labels, X: document embeddings, U: reduced document embeddings, G: tasks and constructs graph, $e^{(1)}$ affinity matrix, $e^{(2)}$ affinity matrix after metapath2vec, C: overlapping community hypergraphs.

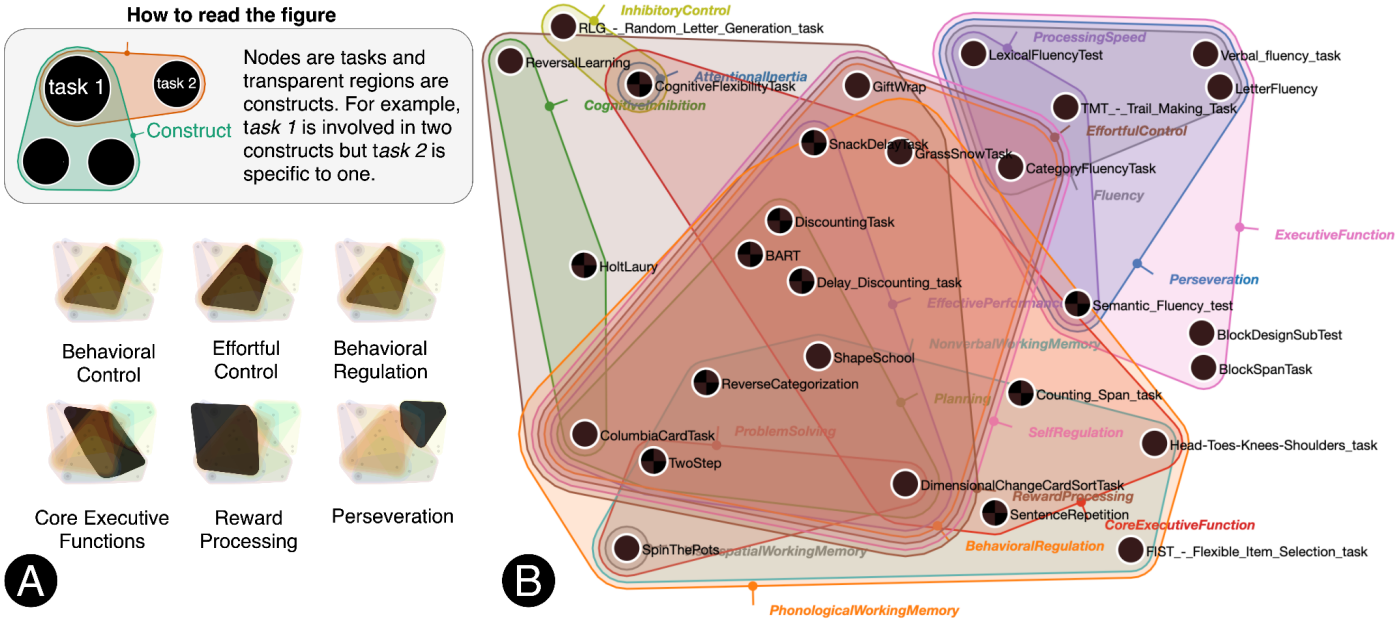

Figure 2. (A) Representations of six control-related constructs as community hypergraphs (B) overlapping hypergraphs reflect construct hypernomy in the construct/task graph; for visual clarity, only a subset of the graph is displayed.

In the proposed graph-based model, similar constructs can be refactored in the graph-based embedding space by defining redundancy as the extent to which constructs can be reconstructed by their neighbors. Moreover, overlapping communities of the final graph reflect the fact that there is no pure task to access complex constructs such as Cognitive Control: every task has the potential to load onto many constructs. It also displays different ways that constructs are manifested in the cognitive science literature. The results call for simultaneous use of multiple tasks to measure or load onto Cognitive Control, while carefully scrutinizing redundant tasks and constructs.

Here we focused specifically on Cognitive Control but this method can be extended to other subdomains within and outside of cognitive science.

References. **[1]** Brick, C., Hood, B., Ekroll, V., & de-Wit, L. (2020) **[2]** Dong, Y., Chawla, N. V., & Swami, A. (2017) **[3]** Diamond, A. (2013) **[4]** Enkavi, A. Z., Eisenberg, I. W., Bissett, P. G., Mazza, G. L., MacKinnon, D. P., Marsch, L. A. & Poldrack, R. A. (2019) **[5]** Baggetta, P. & Alexander, P. A. (2016) **[6]** Angelov, D. (2020)