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Exploring the effect of cognitive diversity, flexibility and interaction interaction on joint semantic search: an agent-based simulation

ABM; social interaction; problem-solving; cognition; semantic search

Extended Abstract

With analogy to animal foraging behavior, it has been suggested that the mental search for ideas, memories, or solutions in problem-solving unfolds as an 'information foraging' process characterized by a succession of *exploration* ("long jumps") and *exploitation* ("short jumps") phases. When presented with a problem, the problem-solver searches for a solution by navigating a mental space of possible solutions analogous to moving through a landscape (Newell, Simon, et al., 1972). Converging evidence points at optimal search patterns being characterized by an alternation between short and long jumps.

The paradigm of cognitive search has been widely used to study individual problem-solving, but many real-world problem-solving tasks unfold in collaborative contexts. Yet, the ways in which social interaction influences search processes remain understudied. It is unclear whether any systematic relationships exists between features of individuals, groups, and interactions structures on the one hand, and search patterns and performance on the other. Challenges in measuring cognitive properties of the group and in tracking the problem solving process online are among the reasons for lack of extensive research in this domain.

Our study investigates computational and social mechanisms of collective problem-solving through agent-based simulations, a computational method which allows for controlled manipulation of cognitive parameters of individual agents and groups, and makes it possible to track online mechanisms underlying search processes. We focus especially on *divergent thinking*, that is, the task of providing as many different and original solutions as possible in response to a prompt, within a set time frame (Gilhooly et al., 2007). Over three experiments, we:

- analyze the effect of inter-individual diversity on joint semantic search;
- analyze whether individual cognitive features – here, cognitive flexibility – interact with diversity;
- investigate how different interaction constraints – strict turn-taking structure, flexible turn-taking, and "competitive" turn-taking – influence performance in the task.

To operationalize semantic search and diversity, we generated individual agents equipped with a "semantic memory", that is, a 400-dimensional Word2Vec model (Mikolov et al., 2013) where vectors for animal names are defined. Based on this semantic model, agents perform a simple association task: they list animal names one-by-one based on immediate proximity in semantic space, until they hit an animal for which no immediate association are available (see Rocca and Tylen, 2022). Agents carry out the task in pairs, taking turns in naming the next animal. We generate 20 populations of agents of increasing diversity. Each population is generated by randomly swapping the position of animals in the agents' semantic spaces, with linearly spaced Euclidean distance threshold defining which pairs of vectors to swap within each diversity level. We measure performance in terms of *fluency* (the total number of animals named, *flexibility* (the average distance between consecutive pairs of animals), and *originality* (agents' ability to reach rarely explored regions of space).

In Experiment 1, we found that, in interactions with strict turn-taking and low individual cognitive flexibility, higher cognitive diversity yields higher fluency, originality, and flexibility, except for extremely high diversity levels (see Figure 1), where diversity seems to be detrimental. This suggests that in contexts where turn-taking is strict, intermediate levels of diversity favors agents' ability to *explore* the search space.

In Experiment 2, we incrementally manipulate agents' cognitive flexibility, allowing them to either go back to the animal named in the previous turn (1-back) or to that named two turns before (2-back) if no immediate association with the last named animal were available. Crucially, increasing individuals' cognitive flexibility mitigated the detrimental effects of high diversity on both fluency and flexibility. Originality patterns change as flexibility increases; different from inflexible agents (0-back), originality is fairly stable for 1-back agents, and decreases as a function of diversity for 2-back agents (see Figure 2). We interpret these results as indicating that higher cognitive flexibility enables agents to counter the downsides of the extremely exploratory search behaviors observed in high-diversity pairs – allowing them to return to more solution-dense areas of the semantic space when their partner pushes the joint search towards solution-sparse regions.

Finally, we observed that manipulating interaction constraints – that is, whether agents are forced to take turns (strict turn-taking), can intervene if the other agent hits a dead-end (flexible turn-taking), or take turns "competitively", with the agents having the shortest association speaking first (competitive turn-taking) – modulates the effect of diversity (see Figure 3). Flexible turn-taking mitigates the catastrophic effects of high diversity on fluency initially observed for inflexible agents, but it also overrides the positive effect of diversity on originality. With competitive turn-taking, diversity still induces positive effects on fluency in this condition, but increasing diversity *reduces* both flexibility and originality. We interpret this as evidence that more competitive and less collaboratively-scaffolded search facilitates convergence towards more "exploitative" search patterns.

Alongside providing novel insights on how cognitive, social, and interactional factors systematically influence semantic search in divergent thinking, our work provides a flexible, controllable, and generalizable method to study the computational mechanisms that underlie problem solving in both individual and collective settings.

References

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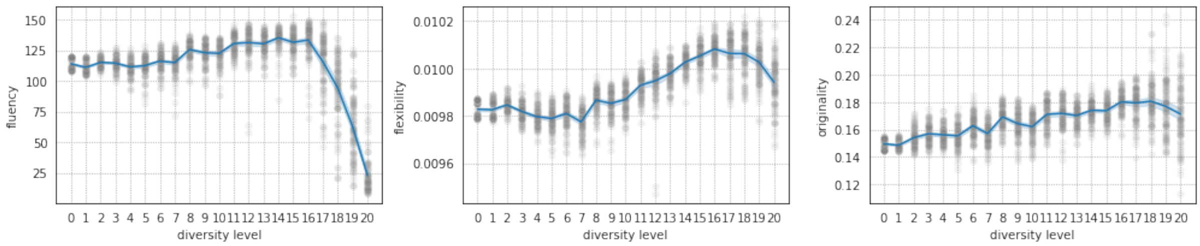

Figure 1: Performance metrics for Experiment 1, interactions with strict turn-taking and agents with low flexibility. From left to right, panels represent fluency, flexibility, and originality.

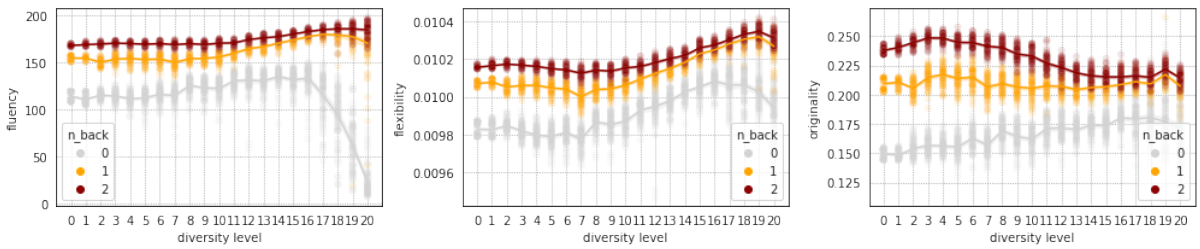

Figure 2: Performance metrics for Experiment 2, interactions with strict turn-taking, varying agent flexibility. From left to right, panels represent fluency, flexibility, and originality.

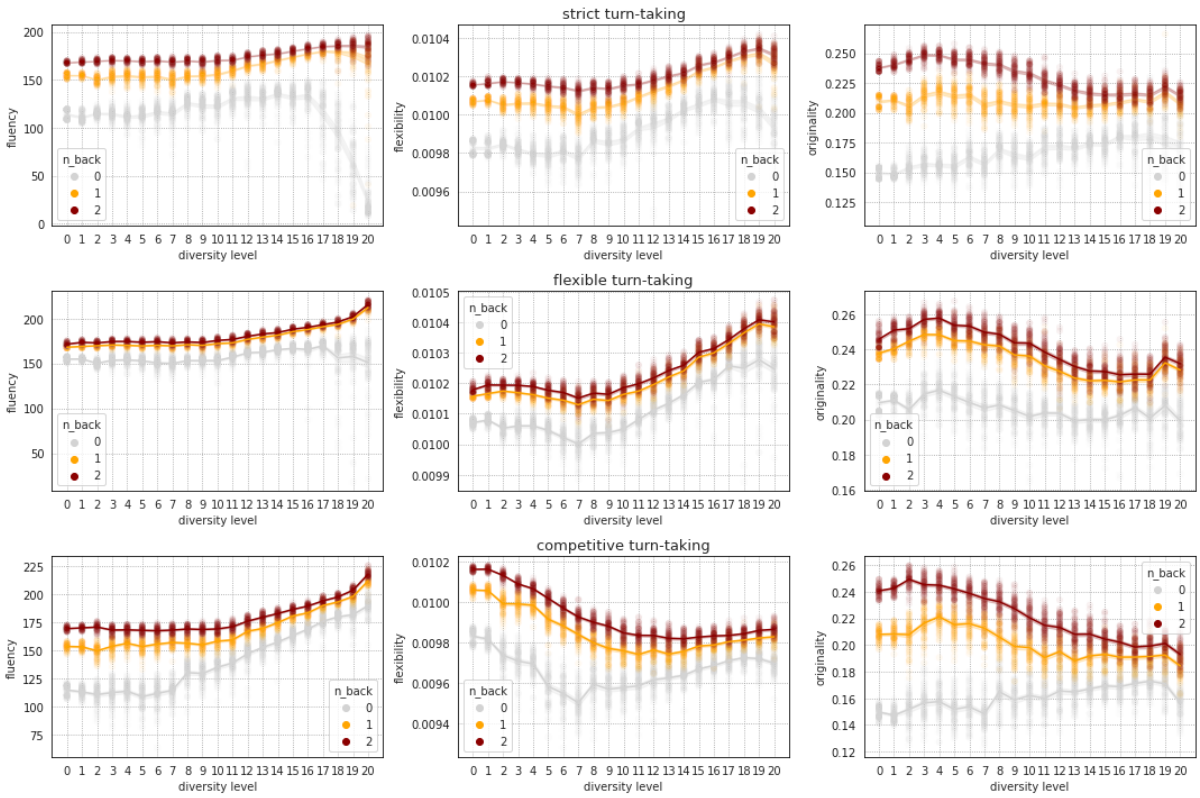

Figure 3: Performance metrics for Experiment 3, varying both agent flexibility and interaction constraints. From left to right, panels represent fluency, flexibility, and originality. Rows represent conditions different interaction constraints.