Diversity and Interaction Structure Shape Performance and Search Dynamics in Joint Cognitive Search: An Agent-Based Simulation

Anonymous CogSci submission

Abstract

Cognitive search, conceptualized as information foraging through mental spaces, underpins many daily tasks and is frequently performed jointly. Yet, the mechanisms by which social interaction impacts search dynamics remain understudied. Through three agent-based simulations of a verbal fluency task, we investigated how cognitive diversity and interaction structure modulate collective performance in joint cognitive search. In Experiment 1, under strict turn-taking, moderate diversity benefited performance by inducing increased exploration, but high diversity levels proved detrimental. Experiment 2 revealed that flexible interaction protocols mitigated these costs by enabling distinct, more adaptive search strategies. Experiment 3 demonstrated that enhancing individual cognitive flexibility via working memory mitigated risks related to high diversity. Collectively, these results identify flexibility, whether situated in social interaction protocols or individual cognitive mechanisms, as a critical route for unlocking the benefits of diversity in collective search, and offer a novel computational paradigm to study the emergent mechanics of collective intelligence.

Keywords: social interaction; cognitive search; cognitive diversity; turn-taking; agent-based simulation;

Introduction

Cognitive search, commonly conceptualized as information foraging through mental spaces, underpins diverse contexts, from ideation to problem-solving, and often unfolds collectively, as a joint exploration of possibilities, solutions, or memories.

While this process is frequently social, modeling efforts have historically focused on the dynamics of *individual* cognitive search. Relying on this foraging analogy, individual search is typically characterized as an alternation between episodes of *exploration* and *exploitation* (Baronchelli & Radicchi, 2013; Hart et al., 2017; Szary & Dale, 2014). People differ in their search strategies with respect to the relative weighting of these two. Some will find more closely related solutions from fewer different domains, while others visit multiple very different domains of solutions while presenting fewer solutions from each domain (Hart et al., 2017). When a task requires an individual to list as many solutions as possible, optimal search has been found to balance the two strategies (Baronchelli & Radicchi, 2013). Yet, little is known about cognitive search performed by two or more agents, and about the way social interaction impacts the structure and dynamics of cognitive search.

Across many different types of experimental tasks, studies have found that individuals interacting to solve problems together can gain performance benefits beyond the better group member (Bahrami et al., 2010; Wahn et al., 2020; Woolley et al., 2015). Yet, different conclusions have been drawn in literature on divergent thinking – that is, the task of providing as many different and original solutions as possible in response to a given prompt, which is an intrinsic component of tasks such as verbal fluency (used in clinical and research contexts, see Ardila et al. 2006; Lezak 2004) and creative ideation (Baer, 2014; Runco et al., 2010). In this context, it has been highlighted that social interaction can also inhibit performance (Basden et al., 2000; Brophy, 1998; Kohn & Smith, 2011; Mullen et al., 1991).

To reconcile these accounts, previous studies have attempted to shed light on *when* and *why* potential performance benefits emerge in interactive contexts. Evidence suggests that benefits may hinge on group members synchronizing or aligning their actions or vocabularies, that is, individuals converging on *similar* behaviors (Fusaroli & Tylén, 2016). Other studies suggest that, when presented with complex problems, groups may benefit from *differences* in group members' expertise, cognitive style or strategies (Aggarwal & Woolley, 2010; Aggarwal et al., 2019; Fjaellingsdal et al., 2021; Hong & Page, 2004; Sulik et al., 2022; Tylén et al., 2023). Groups consisting of members that share similar strategies may in fact be more likely to search similar areas of the solution space, which can constrain the number and nature of their joint candidate solutions. Contrarily, when group members differ in their individual search strategies, they have the potential to broaden their search (Olsen & Tylén, 2023).

Alongside diversity, an additional factor that may modulate outcomes and behavior in joint search is the nature and dynamics of the unfolding social interaction. Collaborative interaction can be structured in a host of ways, with more implicit and spontaneously emerging routines and conventions, or explicitly codified organizational architectures following specific rules. Such 'rules of the game' have been observed to impact the outcome of group processes, possibly due to the way they scaffold, stimulate or impede collective search processes. For instance, groups that spontaneously divide labor in looser forms of turn-taking produce more original solutions compared to those characterized by strict rules or hierarchical leader-follower dynamics (Bjørndahl et al., 2015; Rosenberg et al., 2022; Wallot et al., 2016).

While we possess models of *individual* search trajectories and broad evidence regarding the outcomes of collective interaction, the specific mechanisms by which social dynamics reshape the cognitive search process itself in dyads or groups remain obscure. This is arguably due to methodological challenges. Individual differences in cognitive representations are difficult to quantify and systematically manipulate *in vivo*, and it can be hard to enforce rigid interaction protocols and implement rigorous experimental manipulations in spontaneous real-life social contexts. As a consequence, our understanding of the conditions under which collective performance benefits emerge and of the drivers of such benefits is still very limited. Agent-based simulations can provide a solution for these challenges, making it possible to define and manipulate simplified models of human behavior to study emergent dynamics.

In the present paper, we present a suite a three experiments using agent-based simulations to study the effect of cognitive diversity and social interaction on joint cognitive search. Pairs of agents with varying degrees of cognitive diversity jointly perform a verbal fluency task (henceforth: VFT). In the VFT, participants are instructed to list as many exemplars of a category (e.g., animals) as possible often within a set time frame. Being a task with discrete solutions, performance in the VFT can be straightforwardly operationalized in terms of participants' fluency – that is, how many exemplars a participant names within the set time frame – and originality – the "rarity" of the proposed solutions in a sample or population. The VFT is also uniquely suited to informing discussions about the unfolding search process itself and its underlying mechanisms (Hills et al., 2012, 2015; Kuczma et al., 2023; Szary & Dale, 2014). The list of solutions named by a participant can in fact be analyzed as a trajectory through a computational semantic landscape using semantic distance as a proxy for the exploratory/exploitative behavior.

In Experiment 1, we investigated the effect of cognitive diversity on joint VFT search in a context of strict turn-taking. In Experiment 2, we extended this paradigm to different turn-taking scenarios (a collaborative and a competitive one), to test how diversity impacts cognitive search in more flexible interaction settings. Finally, in Experiment 3, we test how patterns observed in Experiment 1 and 2 interact with the cognitive flexibility of individual agents, by manipulating the individual working memory of the agents in all turn-taking scenarios.

This suite of experiments provides an incremental view on how group diversity, interaction constraints, and individual flexibility influence outcomes in joint semantic search, offering concrete hypotheses for empirical testing in human populations.

Methods

Agent Definition

We instantiated 20 populations of 100 agents each, which we use for all three experiments. Each agent is equipped with a semantic memory constrained to a single domain, that of animals, which is often used in human verbal fluency tests. The semantic memories are variants of an embedding model constituted by vectors for 240 animals (sampled from https://a-z-animals.com/animals/). The *embedding* (or *vector*) *space* was obtained by training a skip-gram word2vec model (Mikolov et al., 2013) on a full dump of the English Wikipedia using the Python package Gensim (Rehurek & Sojka, 2011). Populations are characterized by increasing levels of internal diversity. To operationalize diversity, we add increasing levels of noise to original word2vec semantic space by randomly swapping the position of animals in space. This is performed by setting an increasingly high shuffling threshold. For each agent, we then sample pairs of words in the semantic space that are closer than that threshold, and iteratively swap their position. This approach (as opposed to, for example, adding random noise to vectors), preserves the topology of space across individual agents. As a result, individuals' VFT baseline performance will be the same, and differences can only emerge as a function of interaction with other agents. Procedural and mathematical details on the operalization of diversity are provided in the Appendix.

Simulation Mechanics

Agents perform the verbal fluency task either alone (*individual baseline*) or in pairs (see Figure 1). In the individual case, agents iteratively produce word associations alone, starting from one of the 240 words defined in their semantic memory as prompt. Based on previous modeling of VFT data from human participants (Hills et al., 2015), agents always respond to a prompt (e.g., ''sheep'') by naming the word which is closest to the seed in its semantic memory (e.g., ''goat''). This word, in turn, becomes the prompt for the next association, and this continues until no word has a distance from the current prompt which is lower than a fixed threshold t (*cognitive fixation*), or until all animals have been named. The threshold is set to the 0.15 quantile of pairwise distances (see Appendix for tuning logic). In joint simulations, we randomly pair agents within each population to form 100 agent pairs population. Agents alternate in naming words, using, at each turn, the previously named animal as prompt. In both the individual baseline and the joint task, we run 240 simulations for each agent or pair, each time starting from a different initial prompt.

Experiments

In **Experiment 1**, agents strictly alternate in naming the next animal. Joint simulations end if the turn-holding agent encounters cognitive fixation. In **Experiment 2**, we relax the turn-taking constraints. In the collaborative condition, if the turn-holding agent encounters cognitive fixation, we allow the other agent to become turn-holder and provide the next word. In the competitive condition, at all trials, the agent with the shortest distance between prompt and closest association is the turn-holder and names the next word. If both agents encounter fixation, the simulation ends. In **Experiment 3**, we endow agents with a simple form of working memory, which allows them to backtrack to previous prompts when no sub-

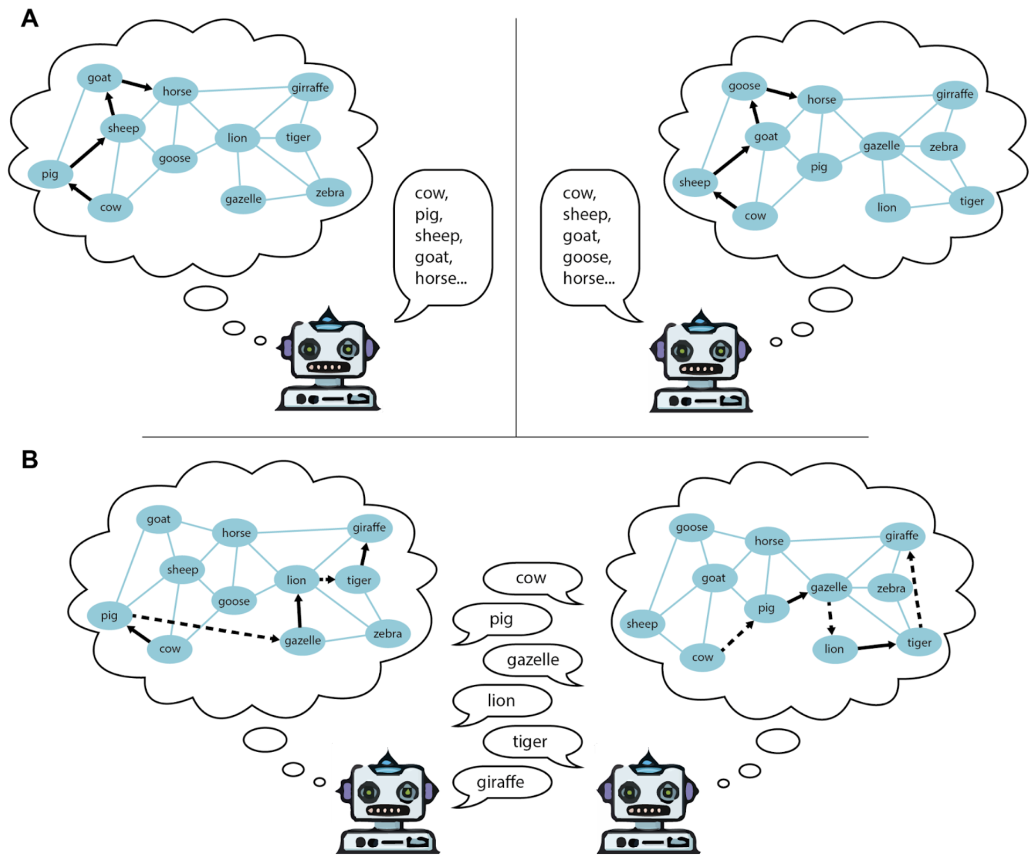

Figure 1: Schematic depiction of the simulation mechanics. A: Two agents performing the verbal fluency task individually. B: The same two agents doing the task collectively. As in the individual condition, the turn-holder names the animal closest to the previously named animal. Yet, as since agents vary in their semantic memories, the resulting trajectories through semantic space are different than what individual agents would produce. Black arrows represent associations made by the agent, dashed arrows are associations made by the partner.

threshold associations with the current prompt are available. We implement two scenarios: one where agents are only allowed to use the previous prompt if the current leads to cognitive fixation (1-back), and one where agents are allowed to go back by up to two previous turns (2-back).

Performance and Search Behavior

We quantify performance using two metrics. **Fluency** measures the total number of words generated (Gilhooly et al., 2007). **Originality** measures the tendency to visit semantic regions rarely explored by isolated agents. It is calculated as the inverse frequency of a word's occurrence in individual simulations, averaged across all steps in a simulation.

We hypothesize that diversity, turn-taking, and flexibility modulate performance by: a) influencing the balance between exploratory and exploitative search; b) modulating agents' likelihood to end up in solution-sparse areas of semantic space. We characterize these dynamics through two additional indices:

- **Exploration Index**: quantifies the average semantic distance between consecutively named words. We distinguish between **active exploration** (average semantic distance between consecutive words relative to the *speaker's* semantic space) and **passive exploration** (relative to the *listener's* semantic space, which quantifies exploration that is merely driven by the partner's behavior).

- **Neighborhood Density Index**: quantifies the tendency to traverse denser clusters of semantic space, computed as the average number of sub-threshold neighbors for each words named in the simulation. We compute this for both the speaker and the listener (to measure the sparsity of the region they are led into by the partner).

While the experiments were planned and conducted sequentially and incrementally, we present the results cumulatively for conciseness.

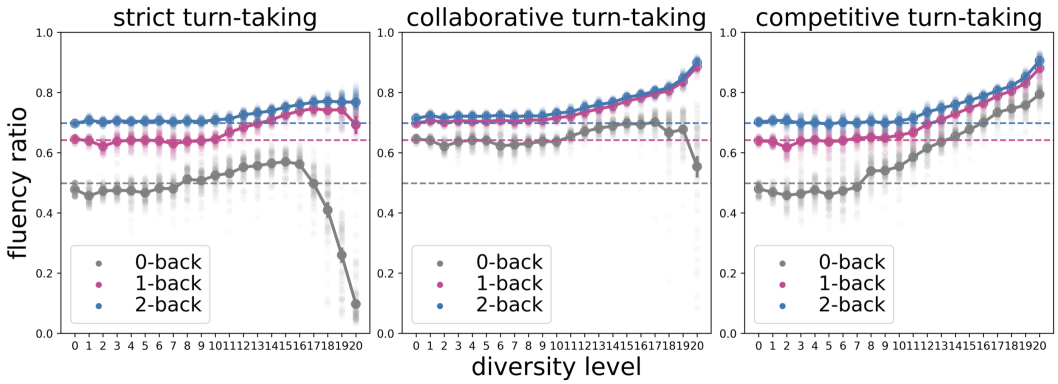

Figure 2: Fluency ratio (average proportion of animals named across simulations by each pair) across turn-taking protocols and n-back conditions in all experiments. Results for **Experiment 1** are the **grey lines, labelled as 0-back, in the strict turn-taking protocols**. Results for **Experiment 2** are the **grey lines (0-back) across all turn-taking protocols**. Results for **Experiment 3** encompass **all data** displayed in the graph. Dashed lines represent the fluency ratios in individual simulations.

Results

Fluency

We first examine how agent diversity impacts fluency. Under strict turn-taking (Experiment 1), diversity exerts a non-linear effect on performance (Figure 2, grey lines in the left panel). Moderate diversity ($10 \leq d \leq 16$) benefits fluency, peaking at $d = 15$ with a ~7% increase over individual performance and ~10% over the baseline group. However, at high diversity levels, performance collapses; at the highest diversity level, agents are only able to name less than 9.2% of the animals defined in their semantic space.

However, Experiments 2 reveals that this collapse is largely due to the rigid interaction constraints of Experiment 1 (see Figure 2, grey lines across all panels). Modulating the turn-taking structure mitigates the detrimental effects of extreme diversity. Specifically, allowing agents to intervene when a partner is stuck (collaborative turn-taking) yields the highest fluency across the spectrum. This protocol buffers against the risk, especially present in high-diversity pairs where semantic spaces are anti-correlated (see Figure 4 in the Appendix for more detail), of agents leading the partner to areas that are extremely sparse for them (see Figure 4). If a speaker leads the group to a semantic neighborhood that is dense for them, but sparse for the listener (leading the listener to cognitive fixation), the speaker can retain the turn and allow the game to continue.

Importantly, these performance gains are accompanied by changes in exploration patterns. In both strict and collaborative turn-taking, exploration increases as a function of diversity (Figure 3). This arguably reduces the risk of *local over-exploitation*, that is, staying in one cluster until it is depleted, which is another possible cause of fixation in low-diversity pairs.

On the other hand, when agents compete for the turn (competitive turn-taking), we observe that high diversity becomes advantageous for fluency even at high diversity levels (Figure 2). This is underpinned by different search dynamics characterized, by protracted individual exploitation (Figure 3), where agents alternate in exploiting their distinct areas of semantic expertise (see also Figure 5 in the Appendix for an illustration).

Finally, in Experiment 3 2, we observe that endowing agents with working memory universally increases fluency and eliminates the performance penalties observed in high-diversity regimes even in the case of strict turn-taking. Working memory mitigates the risks posed by ending up in sparse areas of semantic space, by allowing agents to ”escape” these sparse regions through reverting to a previous anchor word. Thanks to this mechanism, the highly exploratory behavior induced by high diversity does not come with a risk of getting stuck in sparse areas. We also generally observe more exploration for more flexible agents, arguably a consequence of agents resorting to higher-distance associations when backtracking to previous prompts (Figure 3).

Notably, we observe a ceiling effect: as individual agents become more capable (2-back), the collective benefit of interaction decreases. Social interaction effectively induces a form of cognitive flexibility that compensates for individual rigidity; when individuals are already flexible, the marginal utility of collaboration diminishes.

Originality

Diversity consistently boosts originality (Figure 5) across all experiments, with diverse pairs consistently visiting semantic regions more rarely explored by individuals.

When agents are not flexible (Experiment 1 and 2, grey lines in the figure), collaborative turn-taking generally yields the highest originality, particularly at low-to-medium diversity, as – as previously discussed – exploring sparse and thus, less frequently visited regions of semantic space does not incur a risk of cognitive fixation.

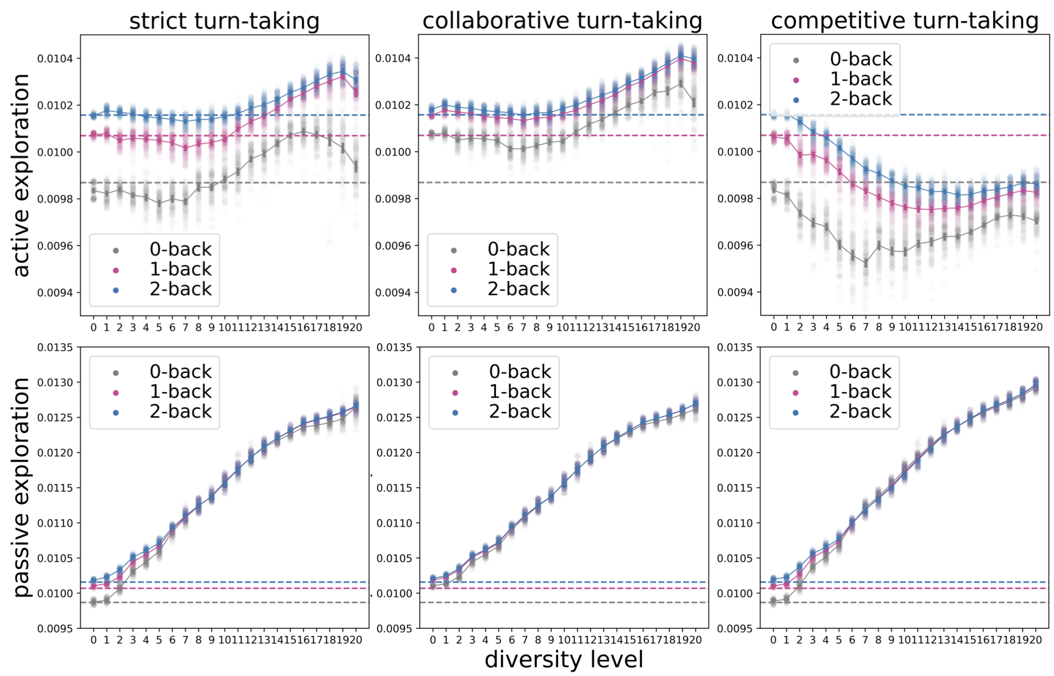

Figure 3: Active exploration and passive exploration across all turn-taking protocols and n-back conditions. Results for Experiment 1 are the grey line (0-back) in the left panels (strict turn-taking) protocols. Results for Experiment 2 are the grey lines (0-back) across all turn-taking protocols. Results for Experiment 3 encompass all data displayed in the graph. Dashed lines represent values from individual performance.

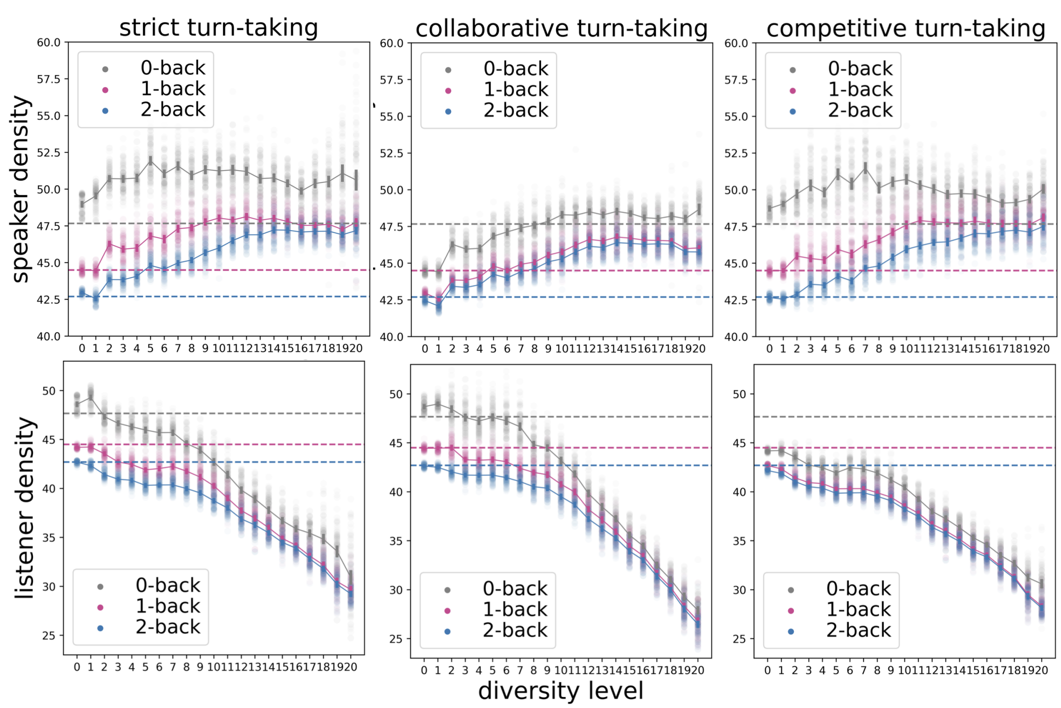

Figure 4: Speaker and listener density for all turn-taking protocols and n-back conditions. Experiment 1 are the grey line (0-back) in the left panels (strict turn-taking) protocols. Results for Experiment 2 are the grey lines (0-back results) across all turn-taking protocols. Results for Experiment 3 encompass all data displayed in the graph. Dashed lines represent values from individual performance.

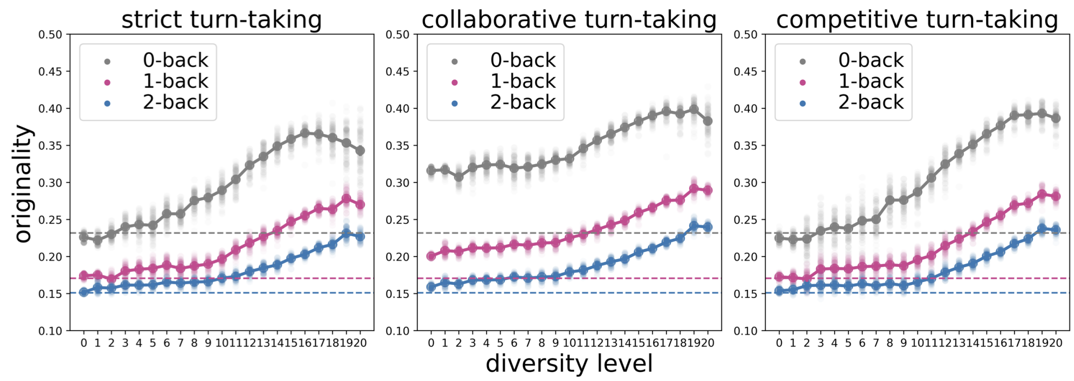

Figure 5: Originality across turn-taking protocols and n-back conditions in all three experiments. Dashed lines represent individual performance. Results for Experiment 1 are the 0-back results in the strict turn-taking protocols. Results for Experiment 2 are the 0-back results across all turn-taking protocols. Results for Experiment 3 encompass all data displayed in the graph.

In contrast, competitive turn-taking yields lower originality, suggesting that while competitive dynamics are efficient for fluency in diverse groups, they drive agents to stay within safe, high-density clusters of their own expertise rather than exploring novel intersections.

Finally, we note that increasing individual cognitive flexibility tends to lower originality. This is a consequence of more flexible agents being capable of reaching more original solutions individually without social scaffolding, and originality being computed on the basis of solution frequency in individual simulations.

Discussion

Over three agent-based simulations, we investigated how group diversity influences performance in joint cognitive search, and whether the effect of diversity is modulated by the turn-taking structures and by the cognitive flexibility of individual agents. We observed that, when agents alternate in naming the next word, diversity is beneficial to fluency and originality, as it enhances exploration and reduces the risk of cognitive fixation by overexploitation of local neighborhoods. Yet, extremely high levels of diversity come at a cost, as they result in agents' being likely to lead their partner to areas of semantic space that are extremely solution-sparse for them. However, simply relaxing turn-taking constraints mitigates or fully overrides these detrimental effects.

Notably, different turn-taking dynamics induce different search patterns, with collaborative turn-taking inducing higher exploration, and competitive turn-taking favoring the emergence of an individualistic search strategy based on agents alternating in protracted phases of exploitation of dense local neighbors. Interestingly, when diversity is very high, this search strategy is highly advantageous for fluency (while reducing the originality of solutions). We also observed that endowing agents with simple forms of working memory is another way to mitigate detrimental effects of high diversity, and to enable agents to more widely explore semantic spaces, including sparser regions, without encountering fixation. Overall, cognitive flexibility seems to be the key to achieving high fluency, be it a property of individual agents, or an emergent property of social interaction facilitated by diversity (Amunts et al., 2020; Rende, 2000; Ritter et al., 2012).

These results provide insights into how, when, and why social interaction and diversity benefit performance in cognitive search, providing testable predictions on the role of diversity and turn-taking for joint cognitive search in humans. Experiments investigating drivers of performance in joint cognitive tasks should consider the effects of pair diversity, turn-taking constraints and individual cognitive flexibility either as target experimental variables, or as factors that constrain the interpretation of final results. Inconsistencies in previous studies may be in fact explained by the systematic effect of unmodelled factors (e.g., interaction protocols, and unmeasured diversity). This is relevant to the study of collaboration in many real-world domains, including the study of creative processes (Rosenberg et al., 2022; Weinstein et al., 2010), or the study of interdisciplinary collaborations (Cox Jr, 2001; Cummings, 2004; Siedlok & Hibbert, 2014).

Our work provides methodological contributions to the study of collective search processes. With our simulations, we present a flexible and innovative paradigm to study social processes from a computational standpoint. Our paradigm can easily be extended to different tasks and more complex forms of behavior, including the use of complex generative language models for more naturalistic interaction scenarios. While our simulations identify key mechanisms linking diversity to performance, translating our findings into a generalizable theory of the effects of diversity and turn-taking on joint search will require additional studies experimenting with variations and extensions of our experimental protocols, including alternative approaches to operationalizing diversity, alternative stopping rules, different tasks, and alternative rules guiding agents' behavior. To facilitate this, we share code and data to reproduce our findings and extend our paradigms as a Python package.

References

Aggarwal, I., & Woolley, A. W. (2010). Do you see what i see? the effect of members' cognitive styles on team processes and performance. *70th meeting of the Academy of Management, Montreal, Canada*.

Aggarwal, I., Woolley, A. W., Chabris, C. F., & Malone, T. W. (2019). The impact of cognitive style diversity on implicit learning in teams. *Frontiers in psychology*, *10*, 112.

Amunts, J., Camilleri, J. A., Eickhoff, S. B., Heim, S., & Weis, S. (2020). Executive functions predict verbal fluency scores in healthy participants. *Scientific Reports*, *10*(1), 11141.

Ardila, A., Ostrosky-Solís, F., & Bernal, B. (2006). Cognitive testing toward the future: The example of semantic verbal fluency (animals). *International Journal of Psychology*, *41*(5), 324–332.

Baer, J. (2014). *Creativity and divergent thinking: A task-specific approach*. Psychology Press.

Bahrami, B., Olsen, K., Latham, P. E., Roepstorff, A., Rees, G., & Frith, C. D. (2010). Optimally interacting minds. *Science*, *329*(5995), 1081–1085.

Baronchelli, A., & Radicchi, F. (2013). Lévy flights in human behavior and cognition. *Chaos, Solitons & Fractals*, *56*, 101–105.

Basden, B. H., Basden, D. R., & Henry, S. (2000). Costs and benefits of collaborative remembering. *Applied Cognitive Psychology: The Official Journal of the Society for Applied Research in Memory and Cognition*, *14*(6), 497–507.

Bjørndahl, J. S., Fusaroli, R., Østergaard, S., & Tylén, K. (2015). Agreeing is not enough: The constructive role of miscommunication. *Interaction studies*, *16*(3), 495–525.

Brophy, D. R. (1998). Understanding, measuring, enhancing collective creative problem-solving efforts. *Creativity Research Journal*, *11*(3), 199–229.

Cox Jr, T. (2001). *Creating the multicultural organization: A strategy for capturing the power of diversity* (Vol. 6). John Wiley & Sons.

Cummings, J. N. (2004). Work groups, structural diversity, and knowledge sharing in a global organization. *Management science*, *50*(3), 352–364.

Fjaellingsdal, T. G., Vesper, C., Fusaroli, R., & Tylén, K. (2021). Diversity promotes abstraction and cognitive flexibility in collective problem solving.

Fusaroli, R., & Tylén, K. (2016). Investigating conversational dynamics: Interactive alignment, interpersonal synergy, and collective task performance. *Cognitive science*, *40*(1), 145–171.

Gilhooly, K. J., Fioratou, E., Anthony, S. H., & Wynn, V. (2007). Divergent thinking: Strategies and executive involvement in generating novel uses for familiar objects. *British Journal of Psychology*, *98*(4), 611–625.

Hart, Y., Mayo, A. E., Mayo, R., Rozenkrantz, L., Tendler, A., Alon, U., & Noy, L. (2017). Creative foraging: An experimental paradigm for studying exploration and discovery. *PloS one*, *12*(8), e0182133.

Hills, T. T., Jones, M. N., & Todd, P. M. (2012). Optimal foraging in semantic memory. *Psychological review*, *119*(2), 431.

Hills, T. T., Todd, P. M., Lazer, D., Redish, A. D., & Couzin, I. D. (2015). Exploration versus exploitation in space, mind, and society. *Trends in cognitive sciences*, *19*(1), 46–54.

Hong, L., & Page, S. E. (2004). Groups of diverse problem solvers can outperform groups of high-ability problem solvers. *Proceedings of the National Academy of Sciences*, *101*(46), 16385–16389.

Kohn, N. W., & Smith, S. M. (2011). Collaborative fixation: Effects of others' ideas on brainstorming. *Applied Cognitive Psychology*, *25*(3), 359–371.

Kuczma, U., Rączaszek-Leonardi, J., & Tylen, K. (2023). Semantic retrieval strategies in divergent thinking. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *45*(45).

Lezak, M. D. (2004). *Neuropsychological assessment*. Oxford University Press, USA.

Mikolov, T., Sutskever, I., Chen, K., Corrado, G. S., & Dean, J. (2013). Distributed representations of words and phrases and their compositionality. *Advances in neural information processing systems*, *26*.

Mullen, B., Johnson, C., & Salas, E. (1991). Productivity loss in brainstorming groups: A meta-analytic integration. *Basic and applied social psychology*, *12*(1), 3–23.

Olsen, K., & Tylén, K. (2023). On the social nature of abstraction: Cognitive implications of interaction and diversity. *Philosophical Transactions of the Royal Society B*, *378*(1870), 20210361.

Rehurek, R., & Sojka, P. (2011). Gensim–python framework for vector space modelling. *NLP Centre, Faculty of Informatics, Masaryk University, Brno, Czech Republic*, *3*(2), 2.

Rende, B. (2000). Cognitive flexibility: Theory, assessment, and treatment. *Seminars in speech and language*, *21*(02), 0121–0153.

Ritter, S. M., Damian, R. I., Simonton, D. K., van Baaren, R. B., Strick, M., Derks, J., & Dijksterhuis, A. (2012). Diversifying experiences enhance cognitive flexibility. *Journal of experimental social psychology*, *48*(4), 961–964.

Rosenberg, M., Gordon, G., Noy, L., & Tylen, K. (2022). Social interaction dynamics modulates collective creativity. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *44*(44).

Runco, M. A., et al. (2010). Divergent thinking, creativity, and ideation. *The Cambridge handbook of creativity*, *413*, 446.

Siedlok, F., & Hibbert, P. (2014). The organization of interdisciplinary research: Modes, drivers and barriers. *International Journal of Management Reviews*, *16*(2), 194–210.

Sulik, J., Bahrami, B., & Deroy, O. (2022). The diversity gap: When diversity matters for knowledge. *Perspectives on Psychological Science*, *17*(3), 752–767.

Szary, J., & Dale, R. (2014). Familiarity modulates the dynamics of collaborative inhibition in a trivia game. *Proceed-*

ings of the Annual Meeting of the Cognitive Science Society, *36*(36).

Tylén, K., Fusaroli, R., Østergaard, S. M., Smith, P., & Arnoldi, J. (2023). The social route to abstraction: Interaction and diversity enhance performance and transfer in a rule-based categorization task. *Cognitive Science*, *47*(9), e13338.

Wahn, B., Czeszumski, A., Labusch, M., Kingstone, A., & König, P. (2020). Dyadic and triadic search: Benefits, costs, and predictors of group performance. *Attention, Perception, & Psychophysics*, *82*, 2415–2433.

Wallot, S., Mitkidis, P., McGraw, J. J., & Roepstorff, A. (2016). Beyond synchrony: Joint action in a complex production task reveals beneficial effects of decreased interpersonal synchrony. *PloS one*, *11*(12), e0168306.

Weinstein, N., Hodgins, H. S., & Ryan, R. M. (2010). Autonomy and control in dyads: Effects on interaction quality and joint creative performance. *Personality and Social Psychology Bulletin*, *36*(12), 1603–1617.

Woolley, A. W., Aggarwal, I., & Malone, T. W. (2015). Collective intelligence and group performance. *Current Directions in Psychological Science*, *24*(6), 420–424.