The Emergence of Collective Intelligence Behavior

PRANAV GUPTA and ANITA WILLIAMS WOOLLEY, Carnegie Mellon University

1. INTRODUCTION

The argument for this abstract can be stated very simply. Any boundedly rational agent aware of their own limitations will come to rely upon their peers so as to collectively reach a higher degree of rationality than possible for an isolated individual. The individuals in such collectives develop metacognitive abilities and interdependent (transactive) processes that allow them to intelligently adapt their psychological decision environment by coordinating the available skills, attention, and goals needed to make these decisions correctly.

1.1 From Administrative to Collective Intelligence Behavior

Simon's seminal work evolved our understanding of an individual's behavior from purely economic or hyper-rational (that assumes complete knowledge, instantaneous processing, and objective reasoning) to administrative or boundedly rational (with limited memory, limited attention, and biased/motivated reasoning) [Simon 1997]. The social organization influences the behavior of boundedly rational individuals by providing them with stimuli or attention-directors that are aligned with organizational goals as well as stable expectations with regards to other members' behavior. One is led to ask, where do these attention-directors and member expectations come from?

Administrative behavior treats the social organization and the individual as independent entities and thereby the knowledge of these influencers (organizational stimuli and others' behaviors) are assumed to be an essential precondition for individual rational action [Simon 1997, p.110]. The Garbage Can Model instantiates this assumption by treating each organizational decision as a result of chaotic/happenstance confluence of problems, solutions, and decision-makers [Cohen et al. 1972]. However, this independence assumption can be relaxed by treating the social organization as a complex adaptive system [Hackman 2012; McGrath et al. 2000] wherein the behavior of the collective emerges from the interdependent behavior of its constituent members. That is, the organization exhibits collective intelligence [Woolley et al. 2010] and the organizational influencers (attention-directors and member expectations) are a consequence of member action which can be characterized by emergent socio-cognitive structure. In essence, this work aims to evolve our understanding of chaotically interacting boundedly-rational individuals (with limited memory, limited attention, and biased/motivated reasoning) to collectively intelligent behavior of boundedly-rational, metacognitive individuals (with transactive memory, transactive attention, and transitive reasoning).

2. THE EMERGENCE OF COLLECTIVELY INTELLIGENCE BEHAVIOR

Recent research by Woolley et al. [2010] established the existence of a measurable collective intelligence (CI) in a team, providing a generalizable metric of a team's ability to perform across a range of tasks. This work emulated the psychometric methodology used in the measurement of individual intelligence, whereby the team was collectively subjected to a battery of fundamental group tasks [Larson 2010; McGrath 1984; Steiner 1972]. Since the original study, the authors have demonstrated that CI is predictive of future performance and correlated with socio-cognitive characteristics such as individual social perceptiveness, amount and distribution of team communication and information sharing, and

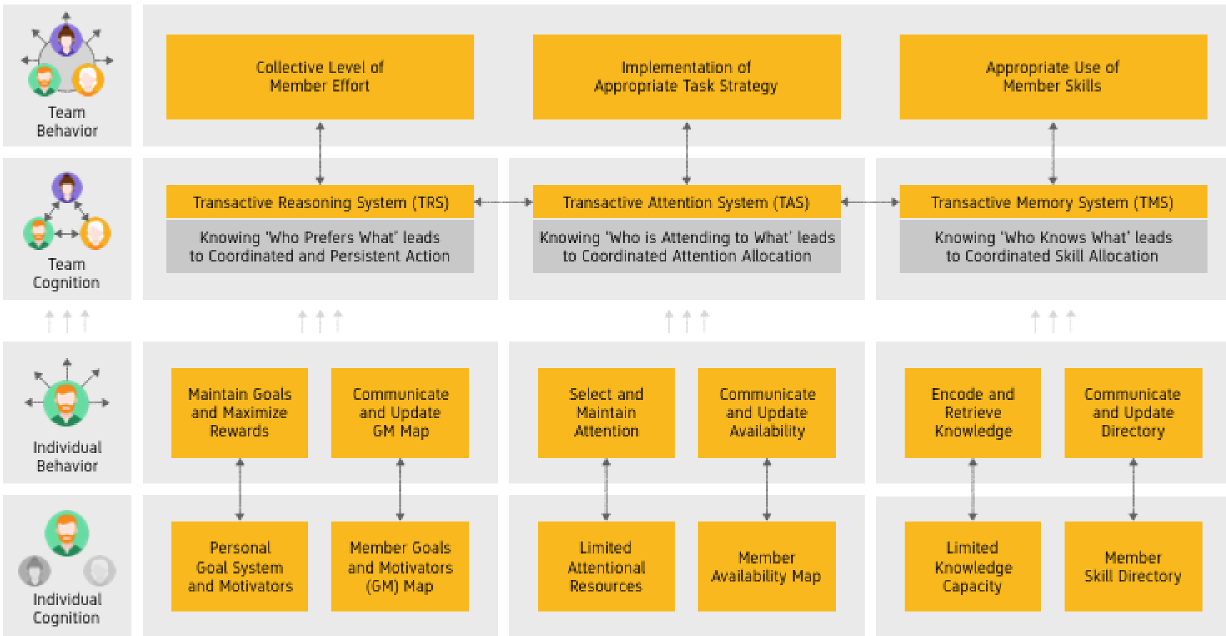

Fig. 1. Proposed Socio-Cognitive Architecture of Distributed Memory, Attention, and Reasoning - Transactive Systems Model of Emergent Collective Intelligence.

the quality of collaboration [Engel et al. 2014; Glikson et al. 2016; Kim et al. 2016; Woolley et al. 2015]. Thus, CI describes the capability of a system to accomplish goals across a range of contexts.

An important question in further understanding CI is whether it is a unitary process that arises as a result of one or multiple interacting, yet distinct, collective socio-cognitive systems. Our analysis of prevailing organizational theory in the previous section points to the latter. Further, decades of research in neuropsychology suggests that among the foundational components of individual intelligence are memory processes and attentional control, along with reasoning [Laird et al. 2011; Luria 1973]. Thus, we contend there is a structural isomorphism to intelligence at different levels of analysis, leading to similar higher-level cognitive functions contributing to the emergence of CI, expressed at the team level as transactive memory, attention, and reasoning systems which manifest in collective decision-making processes. These relationships are captured in our proposed Socio-Cognitive Architecture: Memory, Attention and Reasoning Systems Model of Emergent Collective Intelligence (see Figure 1).

A study of a collective's behavior patterns (temporal and structural) emerging from individual actions and consequent inter-member interactions (transactive processes) has the potential to provide a window into the mechanisms of collective intelligence. Being able to define and layout a framework that describes how these systems interrelate and the conditions under which different socio-cognitive systems outweigh the others in their ability to predict performance would enable us to better understand how the system functions as a whole. *The core propositions of this model are: (1) high intelligence collectives are able to achieve well-developed collective cognition faster than low intelligence collectives, independent of the task environment. (2) All three socio-cognitive systems (memory, attention, and reasoning) have independent as well as joint effects on collective intelligence.* Further, we propose that in the absence of direct measurement of these three socio-cognitive systems, measures of an effective team's performance processes (level of effort, appropriate task strategy, and appropriate use of member skills) [Hackman and Morris 1975; Hackman and Wageman 2005] can prove to be useful indicators of collective cognition.

Below we briefly define and distinguish the three socio-cognitive systems that emerge within an entity exhibiting collective intelligence. (1) Transactive Memory System (TMS) for coordination of *distributed memory*, (2) Transactive Attention System (TAS) for coordination of members' *distributed attention*, and (2) Transactive Reasoning System (TRS) for coordination of members' *diverse goals and motivators* to align their reasoning towards collective action.

Transactive memory system (TMS) is a form of individually-held cognitive understanding of team members' skills, whereby each member not only has an acute awareness of differential specializations or who knows what on the team, but can also credibly rely on these understandings and achieve effective coordination [Lewis 2003]. A TMS can be understood as a form of emergent social cognition - a shared system of encoding, storing and retrieving information across distributed memory while allowing communication via message passing [Wegner 1987]. While the concept was initially developed to characterize the sort of specialization that occurs between couples in close relationships, the concept has since been extended to the group level [Hollingshead 1998; Liang et al. 1995]. Research has already shown that transactive memory systems drive team performance [Lewis 2004] and are strongly related to team collective intelligence [Kim et al. 2016]. In fact, a recent meta-analytic study found that transactive memory systems was more strongly related to performance than the related team cognition construct of shared mental models [DeChurch and Mesmer-Magnus 2010].

While TMS directly addresses the domain-dependent, distributed memory-management processes, no equivalent construct of social cognition has yet been theorized for distributed attention management. In classic team research, the hidden profile problem is a well-understood example of the perils of not attending to relevant information. Groups have been known to disregard relevant information and base their decisions on irrelevant information [Larson 2010]. In any information processing system, the attention of agents puts a hard limit on the capacity of the system to handle information. This central role of attention management (and its relation to interdependencies) in any socio-technical system was a major focus of Simon [1997] and has since carried over to much of the management theory that has developed from that tradition. However, none of these approaches explicate the precise individual-level micro-processes and team-level transactive processes that lead to the emergence of collective attention. This provides the basis for our more recent work on **Transactive Attention System (TAS)** for collective attentional coordination. TAS is a domain-general mechanism through which team members can attract each others' attention as needed while prioritizing and focusing on task-relevant knowledge and goals [Gupta and Woolley 2019]. The core idea relies on the use of meta-attention, a metacognitive ability humans possess that allows them to monitor the attention of other people and identify time periods to grab their attention in a meaningful way [Miller and Bigi 1979]. Meta-attention forms the cognitive basis for the emergence of collective attentional convergence characterized by synchronous behavior which has been shown to be correlated with high CI in teams [Mayo and Woolley 2016]. Furthermore, the proposed transactive processes of 'availability updating' and 'attention allocation' provide a basis for important team processes already discussed in the literature, specifically 'action processes' that involve team monitoring and backup behavior [Marks et al. 2001]. And these transactive processes lead to the progressive use of shared allocation heuristics that is a specific case of team-based shared mental models.

While both memory and attention comprise important processes in teams, there are other important inputs that guide team-level reasoning. One, in particular, relates to team-level goals, and alignment among goals. Research in psychology has already demonstrated that individuals maintain goal systems in their cognition. Individuals select, maintain and, pursue goals so as to fulfill their motivations and maximize overall rewards. A prerequisite for a team (a multi-agent system) to function well together is to be able to self-organize in a manner that their individual goal systems not only capture the system's goal hierarchy but that each member is motivated to pursue the team's goals as well. This dynamic and negotiative (transactive) process of 'goal sense-making' and 'reward alignment' can be meaningfully achieved only if the members are aware of not only their own goal systems and motivators but also its congruence with that of their colleagues. We term this meta-cognitive ability of mapping other members' goals and motivators as meta-rationality and the emergent team-level socio-cognitive phenomenon as **Transactive Reasoning System (TRS)**. TRS is a domain-general mechanism through which team members achieve goal coordination while ensuring meaningful alignment of goals with member motivations. In addition to improved team performance, such alignment also has positive self-regulatory consequences, namely, higher commitment, faster responsiveness, and better affective experiences [Shah et al. 2003]. We propose to develop this socio-cognitive system for transactive reasoning by integrating a diverse body of research, including: (1) Transactive goal dynamics theory that discusses the impact of individual holding and pursuing goals for others [Fitzsimons and Finkel 2018; Fitzsimons et al. 2015] to understand the cognitive structure of meta-rationality; (2) Taxonomy of team processes and their relation to task-based shared mental models [Marks et al. 2001; Mathieu et al. 2000], specifically, the role of transition processes (goal specification and strategy formulation) and interpersonal processes (conflict management and motivation building) to explicate the functions of emergent TRS transactive processes (goal sense-making and reward alignment); (3) AI implementations of meta-reasoning and coordination of meta-level control in a multi-agent system to better specify the benefits and limitations of our transactive reasoning system.

In building on and extending the literature of individual rationality and team cognition we aim to produce a 'Socio-Cognitive Architecture,' possibly the first of its kind. Moreover, our complex adaptive systems approach to emergence of socio-cognitive functions allows for the collectives to exhibit learning over time as well as adaptive resilience to environmental perturbations and internal failures. The characteristics of such an adaptive system can be studied via computational modeling. Much like the Adaptive Control of Thought–Rational [Anderson and Lebiere 1998, ACT–R] and State, Operator, And Result [Newell 1994, SOAR] cognitive architectures that have proven extremely fruitful in the development of Artificial Intelligence, our socio-cognitive architecture holds the potential to be formalized and instantiated in computational terms to deepen our understanding of collective intelligence. Such a socio-cognitive architecture will push the theoretical and practical boundaries of team and organizational design.

REFERENCES

John R. Anderson and Christian Lebiere. 1998. *The atomic components of thought*. Lawrence Erlbaum Associates, Mahwah, N.J.

Michael D. Cohen, James G. March, and Johan P. Olsen. 1972. A Garbage Can Model of Organizational Choice. *Administrative Science Quarterly* 17, 1 (March 1972), 1. DOI:http://dx.doi.org/10.2307/2392088

Leslie A. DeChurch and Jessica R. Mesmer-Magnus. 2010. The cognitive underpinnings of effective teamwork: A meta-analysis. *Journal of Applied Psychology* 95, 1 (2010), 32–53. DOI:http://dx.doi.org/10.1037/a0017328

David Engel, Anita Williams Woolley, Lisa X. Jing, Christopher F. Chabris, and Thomas W. Malone. 2014. Reading the Mind in the Eyes or Reading between the Lines? Theory of Mind Predicts Collective Intelligence Equally Well Online and Face-To-Face. *PLOS ONE* 9, 12 (Dec. 2014), e115212. DOI:http://dx.doi.org/10.1371/journal.pone.0115212

Gráinne M. Fitzsimons and Eli J. Finkel. 2018. Transactive-Goal-Dynamics Theory: A Discipline-Wide Perspective. *Current Directions in Psychological Science* 27, 5 (Oct. 2018), 332–338. DOI:http://dx.doi.org/10.1177/0963721417754199

Gráinne M. Fitzsimons, Eli J. Finkel, and Michelle R. vanDellen. 2015. Transactive goal dynamics. *Psychological Review* 122, 4 (Oct. 2015), 648–673. DOI:http://dx.doi.org/10.1037/a0039654

Ella Glikson, R Harush, Young Ji Kim, Anita Williams Woolley, and M Erez. 2016. Psychological safety and collective intelligence in multicultural globally dispersed teams. Helsinki, Finland.

Pranav Gupta and Anita Williams Woolley. 2019. The Bottom-up Emergence of Transactive Attention System (TAS). Lisbon, Portugal.

J.Richard Hackman and Charles G. Morris. 1975. Group Tasks, Group Interaction Process, and Group Performance Effectiveness: A Review and Proposed Integration. In *Advances in Experimental Social Psychology*. Vol. 8. Elsevier, 45–99. DOI:http://dx.doi.org/10.1016/S0065-2601(08)60248-8

J. Richard Hackman. 2012. From causes to conditions in group research: CAUSES AND CONDITIONS. *Journal of Organizational Behavior* 33, 3 (April 2012), 428–444. DOI:http://dx.doi.org/10.1002/job.1774

J. Richard Hackman and Ruth Wageman. 2005. A Theory of Team Coaching. *Academy of Management Review* 30, 2 (April 2005), 269–287. DOI:http://dx.doi.org/10.5465/amr.2005.16387885

Andrea B. Hollingshead. 1998. Communication, Learning, and Retrieval in Transactive Memory Systems. *Journal of Experimental Social Psychology* 34, 5 (Sept. 1998), 423–442. DOI:http://dx.doi.org/10.1006/jesp.1998.1358

Young Ji Kim, Ishani Aggarwal, and Anita Williams Woolley. 2016. How communication impacts team performance: Exploring collective intelligence and transactive memory system as mechanisms. Fukuoka, Japan.

Angela R. Laird, P. Mickle Fox, Simon B. Eickhoff, Jessica A. Turner, Kimberly L. Ray, D. Reese McKay, David C. Glahn, Christian F. Beckmann, Stephen M. Smith, and Peter T. Fox. 2011. Behavioral Interpretations of Intrinsic Connectivity Networks. *Journal of Cognitive Neuroscience* 23, 12 (Dec. 2011), 4022–4037. DOI:http://dx.doi.org/10.1162/jocn_a_00077

James R. Larson. 2010. *In search of synergy in small group performance*. Psychology Press, New York. OCLC: ocn298181962.

Kyle Lewis. 2003. Measuring transactive memory systems in the field: Scale development and validation. *Journal of Applied Psychology* 88, 4 (2003), 587–604. DOI:http://dx.doi.org/10.1037/0021-9010.88.4.587

Kyle Lewis. 2004. Knowledge and Performance in Knowledge-Worker Teams: A Longitudinal Study of Transactive Memory Systems. *Management Science* 50, 11 (Nov. 2004), 1519–1533. DOI:http://dx.doi.org/10.1287/mnsc.1040.0257

Diane Wei Liang, Richard Moreland, and Linda Argote. 1995. Group Versus Individual Training and Group Performance: The Mediating Role of Transactive Memory. *Personality and Social Psychology Bulletin* 21, 4 (April 1995), 384–393. DOI:http://dx.doi.org/10.1177/0146167295214009

A. R. Luria. 1973. *The working brain: an introduction to neuropsychology*. Basic Books, New York.

Michelle A. Marks, John E. Mathieu, and Stephen J. Zaccaro. 2001. A Temporally Based Framework and Taxonomy of Team Processes. *Academy of Management Review* 26, 3 (July 2001), 356–376. DOI:http://dx.doi.org/10.5465/amr.2001.4845785

John E. Mathieu, Tonia S. Heffner, Gerald F. Goodwin, Eduardo Salas, and Janis A. Cannon-Bowers. 2000. The influence of shared mental models on team process and performance. *Journal of Applied Psychology* 85, 2 (2000), 273–283. DOI:http://dx.doi.org/10.1037/0021-9010.85.2.273

Anna Mayo and Anita Williams Woolley. 2016. Field evidence for collective intelligence in business unit performance. Helsinki, Finland.

Joseph Edward McGrath. 1984. *Groups: interaction and performance*. Prentice-Hall, Englewood Cliffs, N.J.

Joseph E. McGrath, Holly Arrow, and Jennifer L. Berdahl. 2000. The Study of Groups: Past, Present, and Future. *Personality and Social Psychology Review* 4, 1 (Feb. 2000), 95–105. DOI:http://dx.doi.org/10.1207/S15327957PSPR0401_8

Patricia H. Miller and Linda Bigi. 1979. The Development of Children's Understanding of Attention. *Merrill-Palmer Quarterly of Behavior and Development* 25, 4 (1979), 235–250. www.jstor.org/stable/23083944 Publisher: Wayne State University Press.

Allen Newell. 1994. *Unified theories of cognition* (1. harvard univ. press paperback ed ed.). Number 1987 in The William James lectures. Harvard Univ. Press, Cambridge, Mass. OCLC: 247363531.

James Y. Shah, Arie W. Kruglanski, and Ron Friedman. 2003. Goal systems theory: Integrating the cognitive and motivational aspects of self-regulation. In *Motivated social perception: The Ontario symposium, Vol. 9*. Lawrence Erlbaum Associates Publishers, Mahwah, NJ, US, 247–275.

Herbert A. Simon. 1997. *Administrative behavior: a study of decision-making processes in administrative organizations* (4th ed ed.). Free Press, New York.

Ivan Dale Steiner. 1972. *Group process and productivity*. Academic Press, New York.

Daniel M. Wegner. 1987. Transactive Memory: A Contemporary Analysis of the Group Mind. In *Theories of Group Behavior*, Brian Mullen and George R. Goethals (Eds.). Springer New York, New York, NY, 185–208. DOI:http://dx.doi.org/10.1007/978-1-4612-4634-3_9

Anita Williams Woolley, Ishani Aggarwal, and Thomas W. Malone. 2015. Collective Intelligence and Group Performance. *Current Directions in Psychological Science* 24, 6 (Dec. 2015), 420–424. DOI:http://dx.doi.org/10.1177/0963721415599543

Anita Williams Woolley, Christopher F. Chabris, Alex Pentland, Nada Hashmi, and Thomas W. Malone. 2010. Evidence for a Collective Intelligence Factor in the Performance of Human Groups. *Science* 330, 6004 (Oct. 2010), 686–688. DOI:http://dx.doi.org/10.1126/science.1193147