Mnemonic Structure and Sociality: A Computational Agent-Based Simulation Model

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Abstract

How does group memory affect sociality? Most computational multi-agent social simulation models are designed with agents lacking explicit internal information-processing structure in terms of basic cognitive elements. In particular, memory is usually not explicitly modeled. We present initial results from a new prototype called "Wetlands", designed to investigate the effect of group memory structures and interaction situations on emergent patterns of sociality or collective intentionality. Specifically, we report on initial computational experiments conducted on culturally-differentiated agents endowed with finite and degradable memory that simulate bounded mnemonic function and forgetfulness. Our main initial findings are that memory capacity and engram retention both promote sociality among groups, probably as nonlinear (inverse) functions. Wetlands 1.1 is implemented in the new MASON 3 (Multi-Agent Simulator of Networks and Neighborhoods) computational environment developed at George Mason University.

Keywords

Memory, collective intentionality, MASON, Wetlands, agent-based modeling, computational social science.

1 Introduction

Mnemonic storage capacity is fundamental for computational human and social dynamics, because every real-world agent, whether individually or group, necessarily relies on memory—and other internal cognitive structures (such as learning)—to estimate its own state, compute a plan and produce behavioral acts based upon experience.[1] Accordingly, systems of short- and long-term memory are essential—functionally and logically—for retaining and accessing information concerning external situational environments and internal states. Without memory capacity an agent cannot function, making memory a cross-cultural universal for both individuals and cultures. Memory thus links micro and macro scales in human and social dynamics.

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[1]This ontology is based on a view of agents as consisting of knowledge, goals, and behavior/acts. Throughout this paper an "agent" may refer to an individual, such as a single person, or an aggregate of individuals, such as a group, society, nation, or system thereof. However, as explained in Section 2.1, the agents in our computational model (Wetlands 1.1) consist of groups, not individuals.

Interestingly, memory is not uniform across agents, whether individuals or aggregates—groups, societies, or nations—because different agents have different mnemonic structures. Exactly how does memory affect "sociality"[2] or collective intentionality? Is memory significant or secondary for collective action? How do different mnemonic structures—diverse memory attributes such as capacity and retention—affect collective social behavior? How do societies interact when agents have heterogeneous cultural identities? How do mnemonic transformations affect human and social dynamics?

Most computational multi-agent social simulation models are designed with agents often capable of generating collective intentionality, in a generative sense (Epstein, 2004), but computational social agents commonly lack an explicit internal information-processing architecture in terms of basic cognitive structures. Cognitive structures include memory, learning, affect, and other common human cognitive properties. As a result, the "internal environment" (Simon, 1999) of agents often remains a black box.

We present preliminary results from a prototype model designed to investigate the effect of mnemonic function on emergent patterns of sociality or collective intentionality. Our model is intentionally simple in order to easily identify experimental results caused by manipulations of mnemonic structure. Specifically, we present a series of computational experiments derived from an initial model (Wetlands 1.1) populated by group-level agents endowed with memory and bounded rationality. We explore the effects of variations of memory capacity and retention on sociality or collective action.

The following sections of this paper focus on our methods, results, discussion, and conclusions.

2 Method

We are interested in collective intentionality and cognitive processes such as memory and learning. Among the senior authors, we combine expertise in computational social science (Cioffi), computer science and AI (Luke), and computational neuroscience (Olds). Our procedure involved two stages. We constructed an experimental model—the first of several—to generate a minimal but nonetheless interesting artificial society of agents endowed with mnemonic structure and communication, in a simple multi-agent social simulation model called "Wetlands", as described below. We then conducted two initial experiments in Wetlands 1.1 to examine the effects of memory capacity, retention, and simple communication on emergent behavior.

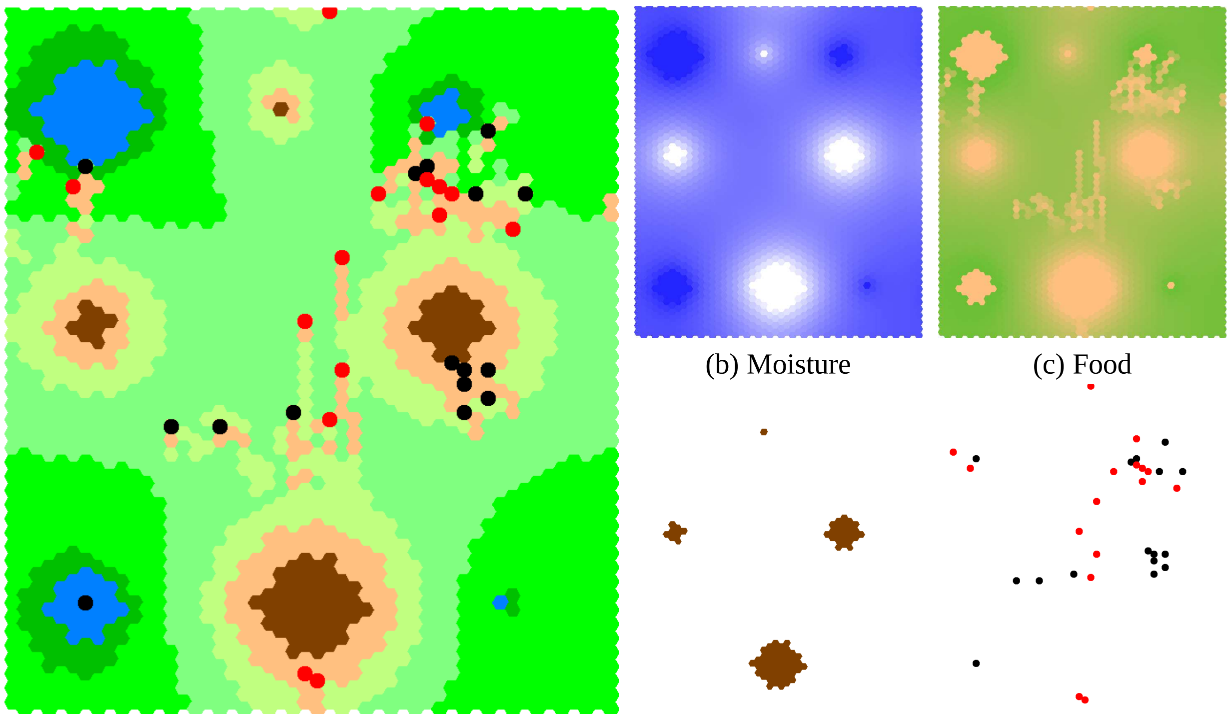
2.1 The Wetlands model

Wetlands 1.1—the agent-based experimental model used in this study—is based on an Sean M. Paus' earlier "Floodland" model (2003) and uses the MASON 3 multi-agent simulation framework for complex adaptive systems.[3] Next we describe the architecture, dynamics, and initial social calibration of Wetlands.

Architecture Wetlands 1.1 consists of a class of situated, autonomous, adaptive, bounded-rational (in the sense of Simon), group-level *agents* interacting at two levels: (*i*) among themselves and (*ii*) with an environment composed of physical *landscape*, simple *weather* (moisture from rain), sites with *food*, and sites with *shelter*. The Wetlands 1.1 landscape is composed of hexagons to avoid the limited orthogonal interaction opportunities of a von Neumann neighborhood, or the arbitrarty corner effects of a Moore neighborhood

[2]"Sociality" means the essence of—what fundamentally constitutes—social phenomena, similar to physicality, chemistry, religiosity, or musicality in their respective domains.

[3]MASON (Multi-Agent Simulator Of Networks and Neighborhoods (Luke et al., 2003)) is an open source simulation core written in Java, available at http://cs.gmu.edu/∼eclab/projects/mason/. MASON is a collaborative project of the Evolutionary Computation Laboratory and the Center for Social Complexity of George Mason University.



(a) Composite (b) Moisture (c) Food (d) Shelter (e) Agents

Figure 1: Wetlands initial visualization and layers. Composite visualization (a) consisting of moisture layer (b), food sites layer (c), shelter sites layer (d), and agents layer (e). Agents are mobile but all environmental components are fixed in Wetlands 1.1 (though environmental components may change in value).

(Cioffi-Revilla, 2002; Gilbert and Troitzsch, 1999). Wetlands' hexagons may be thought of as elementary Thiessen polygons, common for modeling neighboring social interactions among sites or interaction nodes on a regional scale. Socially, each agent in the Wetlands model corresponds to a small *group* of kin-related individuals in a real ("target") world, on the scale of a family or extended family (approximately 2–20 individuals).[4]

Wetlands 1.1 is inhabited by two types of groups (societies), called Atis and Etis, based on the Culture attribute defined on the Group class. Ati and Eti groups are shown in black and red (or black and gray), respectively, in Figure 1a and 1e. In addition to having cultural identity, agents also have memory, such that each group-agent can "remember" at most some N stored engrams which degrade over time. Thus the memory has both a capacity and a retention quality.[5] (In addition, each society—Ati and Eti cultures—will have its own memory in future versions of Wetland.)

Moisture, food, and shelter are randomly distributed over the Wetlands lanscape, as shown in Figures 1b–d. Food grows where landscape has sufficient moisture.

[4]We identify the scale of each computational *agent* in Wetlands as a kin-based *group*, rather than an *individual person*, because all agents exhibit formally homogeneous dynamics in searching for food, shelter, and avoiding rain. Such behaviors are anthropologically (ethologically) consistent with kin-level societal aggregation, not with strictly individual behaviors.

[5]An *engram*, in the sense of Lashley (1929), is a physical (in our case computational) memory trace that records information. Sociologically, an engram can be the computational representation of an *infon*, in the sense of Devlin (1991).

Dynamics Each agent-group goes about searching for food, avoiding rain, and seeking shelter to stay dry. The main simulation loop may be described as follows. Each time-step begins with agents located at various sites in the landscape with a given memory state containing an engram (record) of food and shelter locations stored in memory as an n-tuple. Each agent looks around its neighborhood to acquire additional information on food quality and locations nearby. Besides discovery, information on food and shelter is also acquired through exchange during an encounter (within radius 2) between culturally similar groups (e.g., Ati-Ati or Eti-Eti). Information is not exchanged during encounters between dissimilar groups (Ati-Eti or Eti-Ati), to model the idea of lack of trust between "foreigners" (Polk, 1997). We expect to make further use of this in-group ('we') vs. out-group ('they') feature in subsequent work; here we use it only for simple communication between similar groups.

Fresh information is entered into the agent's memory. If memory is full, then new information will dislodge prior information that is inferior, *even if (by Simon's Satisficing Principle) the new information is only locally (not necessarily globally) superior.* Once memory is updated the agent moves one step towards its preferred food (or shelter — depending on whether or not it is raining). The agent moves towards the "best" food or shelter it remembers, using a weighting scheme which considers both the believed distance from the food/shelter (closer is better) and the "quality" of the food/shelter (higher quality shelter is surrounded by other shelter; high-quality food is based on the moisture content). In a future version of the model, agents' engrams will be degraded through the addition of random noise.

Interactions The main agent-based interactions in Wetlands are (*i*) between agents and their environment (food, moisture, shelter); and (*ii*) among groups of similar or different culture (homogenous or heterogeneous interactions).[6] Memory plays an explicit and key role in each form of agent-based interaction. In the former context (environmental) memory stores qualitative and locational information about food, moisture, and shelter. In the latter context (cultural) memory is updated by—and hence benefits from—homogenous or within-culture contacts. Contact with "foreigners" (dissimilar groups: Ati-Eti or Eti-Ati) (Polk, 1997) does not produce information exchange.

Emergence Based on these minimal simple attributes and rules, we are able to generate and observe two significant emergent collective patterns in the Wetlands artificial world. The first—and arguably most important—consists of *clustering among groups of Atis and Etis*, as shown in Figure 1a. This basic pattern occurs for both feeding and seeking refuge, thereby lending additional external validity to the model—culturally similar groups ultimately tend to seek food and shelter *collectively* as a community (*qua comunitas*), not autonomously, as they spread memories of high-quality food and shelter. The model purposively avoids generating any other more complex social patterns in order to provide a simple experimental bench for conducting memory experiments.

The second significant emergent pattern of collective behavior that is observed is diachronic: after the initial burn-in period of a few hundred time-steps we observe *periodic migrations* between food areas and shelter areas, similar to the daily movement of groups, or the seasonal movement from hunting and gathering regions in the summer to refuge areas in the winter. The food cycle would seem to indicate the former, but in any case the periodic movement of groups is distinct.[7]

[6] Other object-based interactions not involving agents include those between weather (moisture) and food. In Wetlands 1.1 food grows around moisture concentrations and propagates towards arid areas. Moisture regenerates food after agents consume it as they move around the landscape.

[7] We are developing an appropriate indicator of collective migratory behavior to portray collective "swarming" in terms of a time-series metric $M(t)$.

Calibration In relative chronology, the Wetlands target world may be akin to a holocene environment inhabited by paleolithic to early neolithic human groups of hunter-gatherers searching for food to survive and seeking shelter away from rain to protect themselves from the elements. Wetlands 1.1 contains no other phenomenology, making it somewhat comparable to hunter-gatherer models by Reynolds (2002) from a social evolutionary perspective. In addition, Wetlands lacks any explicit technology.

In this study we used Wetlands as an experimental artifact for conducting memory experiments. Other MABSS that display comparable sociality (e.g., Schelling's segregation model, HeatBugs, Sugarscape, and others, Epstein and Axtell (1996), (Gilbert and Troitzsch, 1999, 158–193), Macy and Willer (2002)) are also feasible platforms for conducting similar memory experiments. We chose to develop Wetlands because it provides an initial model for early social evolution with minimally complex and yet interesting collective intentionality ("sociality"), desirable properties for investigating memory.

2.2 Memory experiments

Agent mnemonic structure and dynamics, or how information is maintained and accessed in the short- and long-term memory of an agent, can be modeled in variety of ways as part of an agent's "inner environment" Simon (1999). In this initial study we considered the following two experiments.

Experiment 1: Variation of memory size In the first computational experiment we conducted a series of variations on the agent's memory size. Specifically, we varied the *memory capacity C* of each agent using values of 1, 10, and 25 engrams, to observed whether any effects occurred in the qualitative or quantitative emergence of collective behavior (swarming). Our *research hypothesis* in this first experiment was that greater memory capacity would enhance the probability of collective action, because memory capacity can support a greater volume of inter-agent information exchange. However, the precise form of such co-variation—i.e., whether linear, nonlinear, concave, convex, polynomial, exponential, etc.—is impossible to derive from first principles. Some form of nonlinearity would seem likely (albeit not certain), given the nonlinear properties of information.

Experiment 2: Variation of engram duration In the second experiment we varied *memory retention R* by manipulating the duration of engrams stored in a agent's memory. Our research hypothesis in this experiment was that the longer the time period that engrams would last in an agent's memory, the more efficient the agent's movements—searching for food and finding dry shelter— would be, especially when boosted by information exchange from encountering other culturally similar groups. Operationally, variation in memory retention was implemented by varying the number of time-steps that a given engram would remain stored in memory. In Wetlands 1.1 engram loss was modeled as a simple step function without noise, not as a gradual process (e.g., exponential or logistic memory loss). This will change in future versions.

Other memory experiments We continue to conduct other memory experiments with the Wetlands model, to test for episodic effects, noise, memory loss and degradation, traumatic stress memory disorders, and other cognitive conditions related to mnemonic structure. These will be reported in our final paper. All simulation runs are conducted with MASON 3.

3 Results

Thus far the main results from our computational memory experiments with Wetlands 1.1 can be summarized as follows. Subsequent results will be reported as our experiments continue.

3.1 Emergent sociality and memory capacity

Repeated simulation runs showed that the time required for the emergence of sociality (collective behavior), T, decreased with increasing memory capacity, C, therefore confirming our first research hypothesis. Groups take *less* time to display spatially clustered formations (they start "hanging together" more quickly) when their memory capacity is *greater.* Conversely, they take *longer* to gather as a culture when the lower group-level memory is *low.*

Moreover, our initial results also indicate that the observed negative relationship appears to be both monotonic and nonlinear (concave), with time to emergence T decreasing in approximately inverse and marginally decreasing proportion to memory capacity C, or

$$T \simeq \frac{a}{C^k}, \tag{1}$$

where a and k are scale and shape parameters, respectively, both positive.

3.2 Emergent sociality and memory retention

In terms of our second experiment, repeated simulation runs showed that the time required for the emergence of collective behavior, T, also decreased with increasing memory retention, R. This conformed our second research hypothesis. Here again, groups employ *less* time to achieve spatially clustered formations when they are able to retain memory for a *longer* period of time (number of time-steps). Conversely, groups take longer to "start hanging around together" when their group memory is brief.

In the second experiment our results indicated a similar relationship: the observed negative relationship again appears to be both monotonic and nonlinear (concave), with time to emergence T decreasing in inverse and marginally decreasing proportion to memory retention R, or

$$T \simeq \frac{b}{R^h}, \tag{2}$$

where b and h are scale and shape parameters, respectively, both positive.

4 Discussion

Moving from the specific focus of this investigation to broader considerations beyond the experiments reported here, we now discuss our results in terms of computational findings, broader theoretical implications for sociality and collective intentionality and future research directions.

4.1 Computational findings

Results from this study within Wetlands demonstrate that sociality or the social behavior of groups—for example, groups' propensity to cluster together—is not independent of group-level memory structures and processes. Both memory capacity and engram retention have significant effects on how promptly sociality emerges among groups. Both features also have qualitatively similar effect in terms of increasing the probability of emergent collective behavior (equations 1 and 2).

Verification Our initial Wetlands 1.1 model has undergone extensive verification, so we feel confident about the veracity of the observed experimental effects of memory capacity and retention on the probability of collective action. Nonetheless, we continue to examine the simulation runs closely, to ensure that sociality remains unaffected by bugs.

Robustness Repeated simulation runs of both experiments under different stochastic conditions have thus far failed to invalidate our main results. In the future, we can use MASON's intrinsic separation of computation from visualization to execute a large number simulations runs in a short amount of time to explore the parameter landscape for robustness.

4.2 Theoretical implications

Which theoretical inferences from the computational world of Wetlands 1.1 may be warranted in terms of our computational experiments? Our findings suggests a number of plausible theoretical implications extending beyond "the observed facts" (Lave and March, 1993) in terms of broader social science themes, Simon's Conjecture, and social scale.

A broader social science and ALife perspective So far our research with Wetlands has touched upon half of the six major research themes in Max Steuer's recent assessment of the social sciences, *The Scientific Study of Society* (2003): migration, kin-groups (family), and shelter (housing).[8] While Steuer's survey covers only statistical research on these topics, our computational analysis of the effect of memory on social patterns takes advantage of the unique experimental environment provided by an agent-based model such as Wetlands. Whereas most statistical social science research is based on survey research, even when cross-cultural in scope, computational social science research can contribute new insights through virtual experimentation (Epstein and Axtell, 1996).

In terms of social science and ALife perspectives, our progress with Wetlands so far seems promising, especially in the area of providing cognitive attributes to agents. Experience with Wetlands should also prove helpful as we attempt to generate other emergent patterns of sociality, such as trade or conflict (Min et al., 2003).

Simon's Conjecture Herbert A. Simon [1916-2001] hypothesized that emergent social complexity—observed patterns of sociality and collective intentionality—is caused primarily by the *adaptive* behavior of bounded-rational agents (individuals or groups) interacting in complex environments, *not* by any internal complexity of the agents themselves (1999, 7–8). Social complexity is environmentally induced; not the product of agent complexity ("Simon's Conjecture"). Holland's (1995) approach to modeling complex

[8] The value of Steuer's survey cannot be understated, particularly in terms of highlighting the growth of positive knowledge about society. However, the absence of *conflict* as a major research topic across the social sciences—according to Steuer's otherwise excellent survey—is unfortunate, particularly in light of the growing body of knowledge that exists in this area (Conflict Research Consortium, 2004; Diehl, 2004).

adaptive systems (CAS) is similar: simple agent rules can generate complex emergent patterns if the environment or task is sufficiently challenging.[9] Indeed, one could argue that the epistemology of generative or computational social science is fundamentally based on what may be called "Simon's Conjecture": social complexity emerges from the adaptation of simple agents to complex environments, not from inherently complex agents.

In terms of Simon's Conjecture, thus far our computational findings from the Wetlands experiments—summarized by equations 1 and 2—suggest that complex adaptive behavior (such as social aggregation) could well indeed result from simple internal mechanisms, and—interestingly *and beyond* Simon's Conjecture—*simple linear variations in mnemonic structure* (namely, capacity C and retention R) *cause nonlinear effects* on the timing T of emergent behavioral complexity. This theoretical ("generative") implication is new, based on computational findings, and does not seem to follow (nor arguably contradicts) Simon's Conjecture.

Memory and social scale Scale and complexity are long-standing classical puzzles in the physical and biological sciences (Asimov, 1983; Labrador, 2002; Morowitz, 2002). Unfortunately, social scientists pay less attention to issues of scale and complexity, with some notable exceptions (Eulau, 1996; Schelling, 1971; Singer, 1961; Young, 1998).

Memory is essential to understanding different human and social scales, from individual to societal (and perhaps to global). Our findings offer new insights on multiple scales of sociality. For instance, although agents in Wetlands seem to approximate groups, our results may suggest new research hypotheses on the effect of mnemonic stricture on individual (micro) or supra-group (macro societal) collective behavior.

Formal analysis from computational results From a more formal perspective, equations 1 and 2—which for now we view only as approximate computational generalizations—suggest a number of implications. Both functions represent *power laws* in terms of the independent variables C and R, so their asymptotic behavior is intrinsically interesting.

In addition to formal inferences that can be derived from equations 1 and 2, estimating the numerical value of the corresponding exponents, k and h, is important because such values have implications for the relative (marginal) effects of memory capacity and retention. For instance, knowing even just the values of these parameters (which is larger?) can shed light on their relative importance to derive "dominance principles" (Cioffi-Revilla, 1998, 289). Estimating these and other parameters is possible by running a very large number of fast simulations, a core task for which MASON is designed (Luke et al., 2003).

5 Conclusions

This investigation began by asking the question: How does group memory affect sociality? More specifically, we asked how does memory capacity and the duration of engrams in memory affect the probability of sociality or collective intentionality? Most computational multi-agent social simulation models are designed with agents that usually — or most typically — lack explicit internal information-processing structure in terms of basic cognitive elements. In particular, memory is usually not explicitly modeled.

[9] In computational social science, the view of society as "a complex adaptive system" was formulated shortly after World War II by Karl W. Deutsch (1949, 1951a,b, 1963), under the influence of W. Ross Ashby and Norbert Wiener. Among early pioneering works, see also Buckley (Buckley, 1967, 1968).

We presented initial results from a new prototype called "Wetlands", a multi-agent-based social simulation (MABSS) designed to investigate the effect of group memory structures (such as capacity and retention) and interaction situations on emergent patterns of sociality or collective intentionality. Specifically, we reported on initial computational experiments conducted on culturally-differentiated agents endowed with finite and degradable memory that simulate bounded mnemonic function and forgetfulness.

Our main initial findings are that memory capacity and engram retention both promote sociality among groups, probably as nonlinear (inverse) functions. Wetlands 1.1 was implemented in the new MASON 3 (Multi-Agent Simulator of Networks and Neighborhoods) computational environment developed at George Mason University as a collaboration between the Evolutionary Computation Laboratory and the Center for Social Complexity.

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