# The Concept of Long Memory in Assessing the Global Effects of Augmented Team Cognition

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## Abstract

The concept of long memory is applied to experimental data involving the time series representation of verbal interactions of three team members controlling a simulated uninhabited air vehicle in order to illustrate the utility of a dynamical parameter (the Hurst exponent) for characterizing the long memory of a system, in this case team cognition. A workload intervention is introduced in order to simulate a task redesign. The global effects of this intervention in terms of augmented team cognition defined as long memory processes are identified as a dynamical rule that differentially expands and contracts information structure across team members.

## 1 The Dynamics of Team Cognition

Cognition can be loosely defined as the "process of thinking"; i.e., as a verb, or a cognition can be a "thought"; i.e., a noun. From a cognitive science viewpoint, this is analogous to memory processes and memory structures, respectively. In this paper however, I depart from the conventional viewpoint that these processes and structures are defined over a symbolic state space. Rather, in this paper I will take up the viewpoint that these processes and structures are defined over a dynamical state space, namely the dynamics of *team* cognition. In this regard, long memory processes involve the dynamic information structure (or re-restructure) in terms of various task elements across team members according to a dynamical rule (Gorman, Cooke, & Winner, submitted).

### 1.1 The Concept of Division of Labor

Ostensibly, a division of labor is the concept that individuals are performing different tasks, but tasks that are interrelated for achieving some common goal. Quantitatively, a division of labor involves the amount of mutual information each individual has in common with each other relative to the amount of mutual information each individual has with the overall goal (Gorelick, Bertram, Killeen, & Fuel, 2003). The overall goal corresponding to a division of labor is either known to one or all of the individuals; for example a centralized commander or through a common schema, or it can arise from the local interactions of individuals; it can be self-organized. Whether or not the division of labor involved in team cognition is known or unknown to all team members is a hot area of contention for team researchers with a cognitive science background (see Cooke & Gorman, in press, for a discussion). However in this paper I will circumvent this dispute by assuming that this distinction is irrelevant for understanding augmented team cognition. That is, while useful for assessing local effects concerning a division of labor, the distribution of information concerning overall goals or team member roles is irrelevant for understanding the dynamical processes of team cognition that work at a more global scale. At this level of analysis the division of labor must be viewed as relatively transient. The rule by which the dynamics of a division of labor (or alternatively, information structure across team members) will be considered by assessing the long memory processes of a team, or team cognition.

### 1.2 The Concept of Long Memory

The concept of *long memory* should be distinguished from the concept of *long-term memory*. The latter refers to a mentalistic construct of a symbol storage device derived from a computer metaphor for understanding human cognition. As such, the concept of long-term memory in team cognition involves the static distribution of information stored across team members with an executive controlling device (team mental model) that operates on the information structure. The concept of long memory refers to the long-range autocorrelations of some process, for example the expansion and contraction of reservoirs over long periods of time (Hurst, 1951). As such, the concept of long memory in team cognition involves the long-range autocorrelations of information structure across team members, independent of any sort of executive controlling device or team mental model.

Qualitative long memory processes may involve either positive long-range autocorrelation or long-range negative autocorrelation or zero long-range autocorrelation. Zero long-range autocorrelation is sometimes referred to as a random walk and sometimes as ordinary Brownian motion. Positive long-range autocorrelation is sometimes referred to as persistence while negative long-range autocorrelation is sometimes referred to as antipersistence. Persistent long memory is sometimes called fractional Brownian motion, because of self-similarity across time scales (i.e., fractal structure; Mandelbrot & Van Ess, 1968). Antipersistent long memory is another type of fractional Brownian motion, but in this case it represents a type of self-similarity whereby the whole process is globally bounded. When persistence and anitipersistence are found in the same process, as is the case for all bounded systems, this is indicative of the ebb and flow between the relatively short term *play* in information structure and the nontrivial recurrence of information structure back to a *preferred* state over longer time scales. This is also called positive and negative feedback, respectively, and is typical of bounded self-organizing systems (e.g., control of human posture; Delignieres, Deschamps, Legros, & Caillou, 2003).

Quantitative models of long memory can be constructed by estimating the Hurst exponent, H. The theoretical distribution of fractional Brownian motions attributed to Mandelbrot and Van Ess (1968) is the scaling distribution

$$\langle \Delta x^2 \rangle \sim \Delta t^{2\mathrm{H}};\ 0 < \mathrm{H} < 1, \quad (1)$$

wherein $x$ is the dynamical variable, $t$ is time, and H is the Hurst exponent. This distribution essentially says that the average mean squared displacement of a dynamical variable $x$ is distributed according to varying time scale depending on a dynamical rule, in this case the parameter H. Several qualitative neighborhoods of H are particularly relevant to the concept of long memory. H = ½ corresponds to zero long-range autocorrelation, or a random walk. In this case the dynamical variable $x$ is not persistent over varying time scales such that the process does not exhibit long memory. H > ½ corresponds to persistent long memory, such that the dynamical variable $x$ is independent of (persists over) varying time scales. H < ½ corresponds to antipersitent long memory, such that the dynamical variable $x$ is also independent of (antipersists over) varying time scales. As noted, coupled persistent and antipersistent long memory processes emanating from the same dynamical process represent the positive and negative feedback indicative of self-organizing systems (Figure 1).

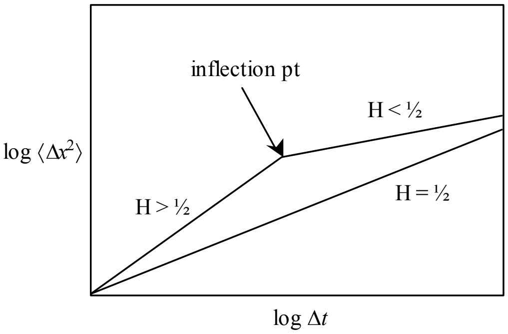

**Figure 1:** Qualitative neighborhoods of long memory from the Hurst exponent for hypothesis testing

It is hypothesized that the dynamics of team cognition likely emanate from a self-organizing system in terms of the dynamics of information structure over team members, rather than a rote information structure that is operated on by a team mental model. This hypothesis will be tested based on an empirical linearization of (1)

$$\log \langle \Delta x^2 \rangle = 2\mathrm{H} \log \Delta t;\ 0 < \mathrm{H} < 1, \quad (2)$$

where $x$ is information structure across team members and $t$ is a non-overlapping time displacement. $H > ½$ coupled with $H < ½$ around an inflection point accord with the stated hypothesis concerning self-organizing team cognition dynamics. A single linear process wherein $H = ½$ accords with the alternative hypothesis, namely that a central executive type mechanism controls information structure at one or another system scaling. In terms of assessing the global effects of augmented team cognition, the inflection point will be inspected as an indication of the global effect of when a team "turns back in on itself", wherein its own dynamics determine a return to a preferred information structure.

# 2 Method

## 2.1 Participants

Twenty three-person teams of New Mexico State University students participated in two 5-hour sessions in an unmanned air vehicle-synthetic task environment (UAV-STE) over seven missions per team. Individuals were compensated by payment of $6.00 per person hour to their student organizations. The three team-members on the highest performing team each received a $50.00 bonus. The participants were randomly assigned to team and role.

## 2.2 Materials

The experiment was conducted in the Cognitive Engineering Research on Team Tasks Laboratory's UAV-STE (Cooke & Shope, 2005). Each team member had a specialized role: Air Vehicle Operator (AVO – pilot), Payload Operator (PLO – photographer), and Data Exploitation and Mission Planning Commander (DEMPC – navigator). Team members coordinated with each other over microphones and headsets in order to "fly" the UAV into position to take photos of ground targets during 40-minute mission scenarios. Teams received performance feedback after each mission. Mission performance scores were based on a weighted sum of several variables: number of photos, mission time, fuel/film used, and time in alarm state. The study presented here was conducted in order to identify differences between co-located and distributed teams under low and high levels of workload.

## 2.3 Procedure

Teams were randomly assigned to either the co-located or distributed condition. In the co-located condition all team members were in the same room. In the distributed condition two team members (pilot and photographer) were in the same room separated by a partition, the third team member was in a different room on another floor of the same building. Teams then received individual role-based skills training followed by a single training mission. Teams flew seven missions total over two separate sessions. The first four missions were low workload while the last three missions were high workload in which the rate of targets relative to the amount of time was increased from 9/40 to 20/40 targets per minute. During each mission communications were recorded in order to later transcribe communications at every mission. These transcripts were submitted for Latent Semantic Analysis for further processing into communication content metrics (Gorman, Cooke, & Kiekel, 2004).

# 3 Results

The average semantic relatedness of team member communications was measured using the LSA-derived cosine between utterance vectors in a high-dimensional space (Gorman et al., 2004). Cosines were averaged across teams for three separate missions corresponding to a low workload initial scenario (Mission 1), a low workload familiar scenario (Mission 4), and a high workload scenario (Mission 5). The averages were taken at seven non-overlapping utterance lags ($t = 2, 4, 8, 16, 32, 64, \& 75$). These lags were determined such that there were at least two sample points for each of the missions. Utterance lags were deemed a feasible replacement for abstract continuous time based on the assumption that sequences of events are the basis for abstract time (Gibson, 1979).

The dynamical rule concerning information structure across team members was estimated using Equation (2). Specifically, $\langle \Delta x^2 \rangle / 2$ was measured using the rescaled-range statistic: $R/S = range_{1\text{-}k}/sd_{1\text{-}k}$, where $k$ observations are available at a given lag. The estimated slope (least squares) of the relation $\log R/S = \log \Delta t$ was taken as the estimate of H. The null line $H = ½$ and the estimates of H by mission are given in Figure 2. The data were obviously not completely amenable to a random walk and they were further analyzed for possible long memory processes. The data were visually inspected in order to infer possible inflection points. Based on the data for Missions 4 and 5 an inflection point at lag 32 was inferred and the data for each mission were compared on this basis. The estimated slopes of the line segments in Figure 2 correspond to the lines of best fit. For persistence lines all $R^2 \geq .94$ for antipersistence lines all $R^2 \geq .68$. For Mission 1, any long memory processes were purely persistent. For Missions 4 and 5 the lines fitted over lags 2-32 are indicative of persistence or positive feedback ($H > \frac{1}{2}$) while the lines fitted over lags 32-75 are indicative of antipersistence or negative feedback ($H < \frac{1}{2}$). These long memory processes were most pronounced for Mission 4.

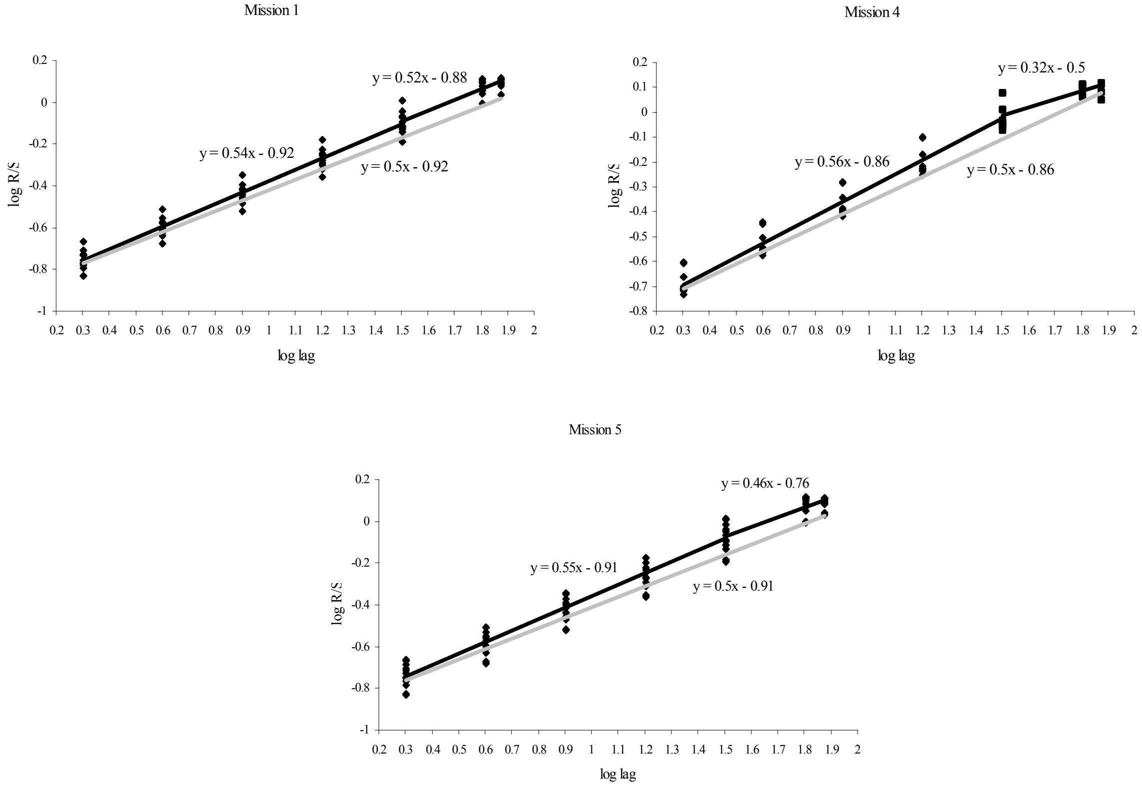

**Figure 2:** Estimates of long memory processes from team communications over two low workload and the one high workload UAV-STE missions

# 4 Discussion

The long memory processes involving UAV-based semantics over the two low workload missions indicated that the "boundaries" of the system had to become established, considering the change in long memory processes from Mission 1 to Mission 4. Once these processes were established, information structure followed a similar dynamical rule over both Missions 4 and 5 whereby teams exhibited a degree of persistence in information structure over relatively shorter lags and antipersistence at the longest lags. This is indicative of a self-organizing process such that positive and negative feedback were involved in the short term *play* in information structure coupled with the long term recurrence of a *preferred* information structure over longer lags. The differences in long memory team cognition processes identified between Missions 1 and 4 were likely due to the fact that the dynamical rule was emergent and thus perhaps more entrenched by Mission 4 in governing the local interactions of team members. Missions 1 and 5 consisted of new, unfamiliar scenarios. In Mission 5 the dynamical rule was similar to Mission 4, but less developed, similar to Mission 1. Given the novelty of the scenario, it may be the case that any sort of low-dimensional long memory processes that develop over time were affected by the high workload intervention that augmented the team cognition memory processes. However this interpretation is fairly speculative and more work needs to be done to establish whether or not this difference is important, and if so, to explain the differential effects.

# 5 Conclusion

What is perhaps wholly most significant about the results presented here is that team members are likely unaware of the dynamical rule involving information structure, or in this case the long memory processes constituting team cognition. In this regard, team cognition can be considered an *emergent property* of the UAV-STE system rather than the static distribution of information across team members in terms of roles. That is, a globally determined low-dimensional process emerges that constrains information structure over long-range time scales. This result has several theoretical and practical implications for assessing the global effects of augmented team cognition. First, team cognition may best be defined over a dynamical, rather than symbolic, state space. The semantic content of UAV team members operates over a symbolically defined state space. However the results presented here identified a dynamical rule, in this case long memory processes, that literally subsumed the symbolic state space by constraining it over long time scales. Second, although no *major* differences in the dynamical rule were identified using the high workload task intervention, the results support the notion that the effects of augmented cognition can feasibly be studied at the global level of team cognition rather the local level of symbolic team member knowledge. Ultimately these results support the notion that information structure in teams follows a dynamical rule rather than local operations via team mental models on a statically defined symbol system. This approach to understanding team cognition, and specifically the effects of augmented team cognition, has never been attempted and represents a new way of approaching the problem. While perhaps an important aspect of the current paper, this very novelty suggests that much work still needs to be done in order to refine the approach. In any case, the concept that a dynamical rule emerges unbeknownst to the team members opens up some promising theoretical and practical avenues for assessing the global effects of augmented team cognition.

# 6 Acknowledgments

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