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A View of the Combat CAS: Unifying Net-Enabled Teams

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Abstract

This paper summarizes the results of a series of controlled Human-In-The-Loop experiments with teams of distributed warfighters engaged in combat scenarios enacted on wargame simulators. When viewed in the light of complexity theories, the significant results demonstrate some important empirical regularities. They show generally that increasing the self-similarity of a CAS (Complex Adaptive System), or warfighting team, composed of agents, or individual warfighters, with respect to their shared decisionmaking processes and shared schema of the battlespace, serves to increase the quality of their shared mental models, including situational awareness and plan quality, and thereby increase the combat effectiveness and agility of the team as a whole. The series of experiments shows, first of all, that teams sharing a common network, decisionmaking processes and broadened schema of the battlespace increase their self-similarity by moving from use of Local Tactical Picture schema to a Common Operational Picture (COP) schema, thus enabling all team members to share a common input. This initial alignment results in significantly increased situational awareness, shared situational awareness, and combat effectiveness for the entire team. Then moving from COP to Collaborative COP, thus enabling a shared common planned output from the team and shared feedback of results on the COP, yields further significant increases in situational awareness, shared situational awareness and combat effectiveness and agility for the warfighting team as a unit.

Introduction

Consider a commander with a warfighting team about to engage in combat with an adversary. The commander and his team must first size-up the battlefield situation and then develop a course of action (COA) to carry out their combat mission. In order for the commander and team to gauge the situation accurately, they must gather and share information from and about the real world battlespace and convert this information into veridical perceptions, relevant cognitions and overall awareness of the battlespace; otherwise they cannot act effectively. We shall show that these tasks are best accomplished within a socio-technical system composed of humans and certain information technologies: Some information technologies enable more effective team action than others. In general, information technology that provides the team a compressed and widely shared view of the battlespace, both actual present and possible future, coupled with the capability to conduct discourse about these states of affairs enables improved combat effectiveness. It accomplishes this, in large part, by fostering a more accurate situational awareness which is widely shared among team members, and by facilitating the development of better plans for synchronized action by the team members.

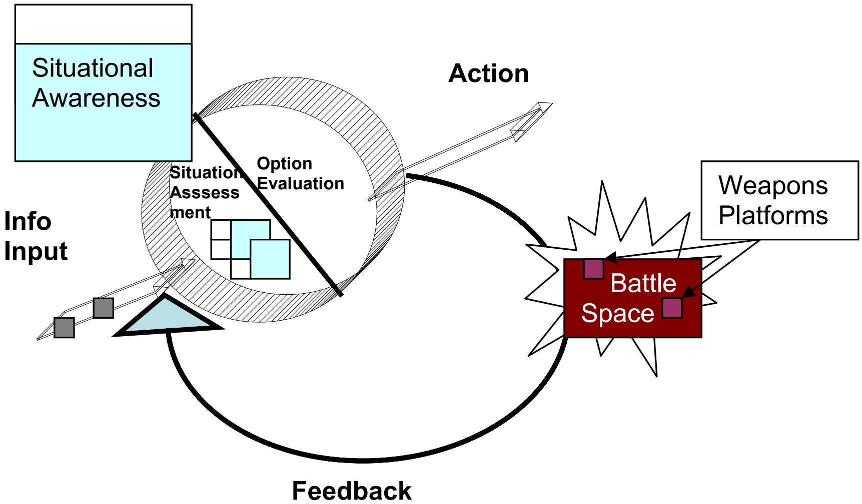

Figure 1. Individual agent's decision loop.

The Combat CAS

It is useful to conceive of the warfighting team, either distributed or local, as a Complex Adaptive System (CAS). A CAS is a complex, self-similar collection of interacting adaptive agents. In adapting, the agents of a CAS typically act in parallel, constantly acting and reacting to what other agents are doing. The resultant order is emergent, rather than predetermined or ordered from above, i.e. the agents are self-organizing. Such CAS exhibit a high degree of adaptive capacity, providing resilience or agility in the face of perturbations (Waldrop 1992). In achieving such adaptive capacity, agents of the CAS make use of schema, viz. a shared representation among the agents of the CAS of the relevant aspects of the external environment, providing descriptions, predictions and prescriptions for effective, adaptive actions in the environment (Gell-Mann 1994).

When applied to a warfighting environment, such an approach involving CAS has been termed Network Centric Warfare. It focuses on the combat power that can be generated from effective linking or networking of the warfighting enterprise. It has been characterized as the ability of geographically dispersed forces to create a high level of shared battlespace awareness that can be exploited by means of self-synchronization and other network centric operations to achieve commander's intent (Cebrowski and Garstka 1998; Alberts et al. 1999, 88). We shall show that increasing the self-similarity of the agents of the CAS with respect to their decision making processes, including shared schema of the battlespace, promotes the causal linkage between shared battlespace awareness and effective self-synchronized action and agility by the warfighters. We shall focus here on the small distributed warfighting team as a CAS composed of individual warfighters as agents.

As depicted in Figure 1, a single agent, such as a commander or another individual warfighter, makes combat decisions by scanning the environment for relevant information, sizing up the situation, developing and evaluating his/her options, acting on one of them, and receiving feedback on the consequences of these actions. The better the individual's situational awareness, e.g. of the location and identity of relevant weapons platforms in the battlespace, and the better the planned action, the more effective the individual should be. This is a commonly used decision cycle[1] framework. Here we have

1. Many investigators have set forth versions of the command decision cycle. Since John Boyd originally proposed the OODA loop (Observe-Orient-Decide-Act) process to represent the decision cycle of pilots engaged in air combat scenarios, several variations have been developed in differing contexts. For the SHOR paradigm (Stimulus Hypothesis Option Response) see (Wohl 1981) The HEAT paradigm (Headquarters Effectiveness Assessment Tool) is described and used in (Sovereign and Stewart 1986) and more extensively in (Hayes et al. 1983). The HEAT model looks at the speed and accuracy of the decision cycle composed of six phases: monitoring, situation assessment, course of action development, outcome prediction, decision, directing of action...remonitoring. The HEAT decision cycle or "planning cycle" occurs at the level of the larger organization, e.g. under a Theater Commander; the OODA Loop decision cycle

expanded the focus from the individual decision maker to a similar decision cycle employed by an entire team composed of several warfighters. As depicted in Figure 2, the combat team as a whole that we consider is self-similar to the members (agents) of the team with respect to sharing common combat decisionmaking processes and common informational schema within and across the team.[2] Such a collection of warfighters comprises a combat CAS. In a Net Centric Warfare (NCW) CAS condition, warfighter agents pool, over a shared network, their individual sensor reports, e.g. ship's radar hits, together with information from national intelligence sources, to a common shared picture (or schema) of the battlespace; and different warfighting agents also lend defensive (and offensive) shooter actions to support other team members, in accord with collaboratively developed and shared plans[3].

is at the level of the individual warfighter; here we consider the in-between level of the group, e.g. crisis action team. It is noteworthy that if all "strategic" or big picture information is hoarded at the top level of the organization or if only partial, special interest information is sent to lower levels from top levels, then the sub-groups within the larger organization are not self-similar to the organization as a whole, and taken together they do not comprise self-similar agents of a CAS; indeed, the decision cycles of individuals within the larger organization bear small resemblance, content wise, to those of the organization as a whole. If one thinks of groups within larger "edge organizations" that possess decentralized command, relatively unconstrained interaction among teammates and broadly distributed information, there is a greater possibility of self-similarity of the groups as agents to the larger organization (See Alberts & Hayes 2003). In terms of information technology, it is noteworthy that the COP brings strategic information normally retained at high levels down to lower level units, i.e. the COP contributes to flattening the warfighting organization; similarly, the collaborative COP further contributes to flattening the organization by facilitating peer-to-peer communications.

2. A self-similar object is exactly or approximately similar to a part of itself.

3. In the original treatment, Network Centric Warfare (NCW) referred to placing emphasis on information and information technology to enhance effectiveness in combat operations in comparison to the traditional emphases placed upon (weapons) platform based warfare (See VADM Arthur K. Cebrowski and John J. Garstka., "Network Centric Warfare: Its Origin and Future," *Proceedings*, 1998).

We hypothesize that this sharing of schema and decision processes, this staying on the same sheets of music for informational inputs, concerted action outputs and feedback of results, as it were, by the individual agents leads to emergent properties for the CAS as a whole consisting of broadly shared situational awareness, widely shared plan view and increased combat effectiveness over and above that achieved by more loosely coupled, freewheeling agents comprising a simpler multi agent system, tuned to different drummers. Thus in sharing situational awareness, the agents of the CAS should more rapidly arrive at a consensus on the locations and identities of the mission critical warfighting platforms in the battlespace situation. Indeed the common sheets of music are best played, not by a chief and his ministers, but by a "band of brothers," as it were. The greater the sharing across the agents of common decision processes, with common inputs and common (planned) outputs and common feedback of results all utilizing common schema of the battlespace, and the greater the sharing of situational awareness, the greater the self-similarity of the CAS, and the greater the combat effectiveness for the CAS as a whole. The emergent group phenomenon portrayed here is not unlike the transition from the rhythmic actions of a single soldier responding solely to the shouts of a drill sergeant to those of the magnificent ensemble of an entire drill team responding to the sergeant's shouts and to each other in an echoing unison. We also hypothesize that another emergent property of such a CAS, information load sharing, aids in mitigating the information overload constraints (See Levis et al 1987, on "bounded rationality"), in both situation assessment and plan enactment, posed by the well established cognitive limitations of the individual human agents through a raising of the information overload crash threshold for the team as a whole to a level above that for any individual agent. Thus, consider the case where a ship captain is besieged by many incoming enemy aircraft or fast attack boats which one must promptly identify and deal with appropriately. Sharing common schema and decision processes with teammates should enable the individual to hand off, or "off-load," certain of these incoming threat responsibilities to well positioned team mates, perhaps depending on the geographic sector from which the attacks are originating, so that the individual, alone, does not become overwhelmed. As a corollary, we hypothesize that the CAS should exhibit more resilience or agility in maintaining combat effectiveness by recognizing and reacting to rapidly changing or complicated situations posed by an adversary.[4] Thus a warfighting team's agility should be improved by information technologies that improve the situational awareness or replanning quality of the agents composing the CAS.

In examining the implications of this approach we shall first examine the kinds of informational schema, such as battle maps, that are shared by the warfighter agents across the CAS. Next we shall venture to the psychological level to examine the shared mental models of the warfighters, such as shared situational awareness of the battlespace, that are responsive to the shared informational schema and helpful to the adaptive actions of warfighting team. At this same cognitive level, we shall then further examine the individual human limitations in information processing and how these may be mitigated by collaboration with teammates. Finally, in investigating the determinants of combat effectiveness of such a CAS we shall bring to bear some evidence from controlled experiments with teams of distributed warfighters on the role of broadened shared schema in impacting the combat effectiveness of warfighting teams via improved shared mental models of the battlespace.

4. For a broad treatment of C2 research which leads the way in emphasizing the importance of the concept of agility in the future of C2 see Alberts (2007).

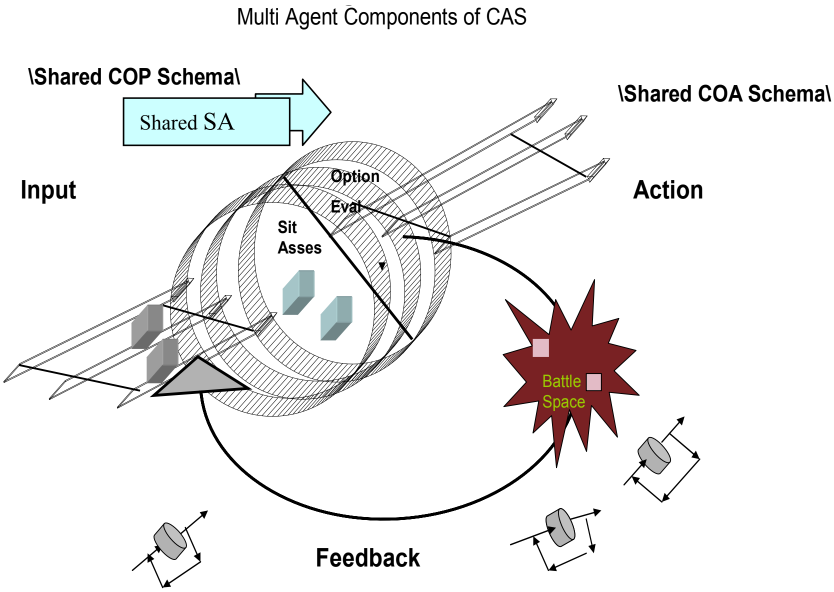

Figure 2. CAS composed of self-similar agents.

Schema Shared Across the CAS

The team members or agents of the CAS may share various levels of informational schema. The collaborative UDOP[5] capability, for example, provides shared schema, or models, for the members of the warfighting team, i.e. shared representations inside the warfighting team of the relevant aspects of the external environment (Hiniker 2002). In general, these shared representations or "schema" provide

5. UDOP (User Defined Operational Picture), which facilitates the tailoring of special views within the larger COP, is one of the important capability modules of information technology, providing new "schema" for the warfighter. It is being systematically engineered as a part of the Net-Enabled Command Capability (NECC) Program of DISA. It represents a further evolution of the Common Operational Picture and, when used in conjunction with Net Centric Enterprise Services (NCES) collaborative whiteboard capability, offers important new mission related capabilities for the warfighter.

a CAS with descriptions, predictions, and prescriptions for effective interactions in the environment (Gell-Mann 1994; Gell-Mann 1997). With better compressed schema or models of the external environment, the CAS can better adapt to changes in the environment; it can better pursue its goals; and it has better fitness or chances of survival in its environment. Thus better schema of the battlespace provides better, i.e. more accurate or more complete, descriptions, predictions, and prescriptions for the warfighter. For example at a high level, in the information technology provided by the collaborative UDOP battlespace map schema, i.e. the Collaborative COP, the COP represents the current situation; and the whiteboard permits shared graphic representation of hypothetical future planned situations in the battlespace, yielding an even greater level of self-similarity of schema within the CAS and across the agents or team members by adding the dimension of a shared representation not only of the present situation but also of possible future situations. At the lowest level of schema sharing we consider, there is no Common Operational Picture (COP) of the battlespace shared across all members of the team, but only an individual Local Tactical Picture (LTP) view fed by sensors that are organic to the warfighting platform commanded by the individual agent; the individual agent can then communicate, or share, his/her observations with teammates, but only verbally. Thus three cumulatively broader, more encompassing levels of schema of the battlespace for the CAS are considered here: Local Tactical Picture (LTP) fed by organic sensors only; Common Operational Picture (COP) of the current battlespace fed over a network by organic sensors from several platforms as well as national intelligence sources, enabling the team to share a common input; and Collaborative COP (CCOP) of the current and possible future situations in the battlespace, enabling the team to construct and share a common plan for action output and to share common feedback of the results of that action on the COP.

Historically combat schema have not been carved into stone tablets; rather they have changed with experience. By virtue of interactions with other CAS, under controlled or accidental conditions, a CAS may evolve improved or "fitter" schema better to adapt itself to its environment. Some human crafted schemata, such as the 1300 B.C. map of the Babylonian city of Nippur (in present-day Iraq), were carved into clay tablets, but the ancient battlefield map is one type of schema that has obviously evolved extensively over the centuries. It has moved from cryptic annotations on parchment representing the gross locations of own and enemy forces carried on horseback from one troop location to another; through relatively sophisticated drawings of the battlefield, e.g. the Smithsonian's Battle of Saratoga Map (September 10, 1777), with considerable details of General Burgoyne's red and General Gates' blue shooter locations made during our Revolutionary War era; to the rapidly evolving, rapidly updated, electronic maps of the battlespace in use by our modern warfighters (See Hiniker 1998). Essentially the Common Operational Picture provides a zoomable map view, fed by multiple sensors, of the near real time locations (latitude-longitude and sometimes depth or elevation) of the weapons platforms (ships, planes, etc.) or troops in a bounded battlespace area and descriptions of the identities, in terms of weapons type and side (blue, red or neutral) of these weapons platforms. It also provides, where available, movement vectors for air craft and sea craft in the battlespace as can be discerned from multiple sensor readings recorded at various times on the locations of the observed weapons platforms. The near real time input to the COP provides a timely informational basis for decisionmaking by a combat team greatly surpassing that provided by traditional battle maps. Thus the schema for a "combat CAS" has evolved to fitter schema in real and simulated warfare, and under natural and controlled conditions. Such evolution is expected to be more rapid in systems located "near the edge of chaos," such as in some of the simulated combat scenarios we consider here in examining the evolution of some information technologies under controlled experimental conditions later in this study.

We have focused here on schema of use on the interpretive side of the CAS; the CAS, and its agents, also employ schema containing action rules for prescribing COAs for mission accomplishment by the CAS, often linked to certain frequently appearing situational patterns. More schema development along these general lines is available in the work of Holland (1994).[6] In the combat area, wargame simulators provide one potential means of evaluating and prescribing COAs for warfighting teams.

Such informational schemata[7], representing the relevant aspects of the changing situation and what to do about it, form the major portion of the relevant message traffic passed around the communications network, and taken together these messages constitute replicas of the state of the command decision process, itself (See Girard, 1990). For the most part, in this "information world," observations and assessments come in and go up; plans and directives come down and go out[8] (See Figure 3).

Shared Mental Models within the CAS

When internalized by human warfighters, the shared informational schemata constitute shared mental models (Rouse and Morris 1986), and should enable the warfighting team, conceived of as a unified CAS, to complete the synchronized individual or group decision cycle (or group OODA (Observe-Orient-Decide-Act) Loop process) more rapidly and effectively leading to greater combat effectiveness.[9] The common inputs, shared picture of the battlespace, common

6. For a focus on schema, or internal model, as a set of rules enabling an agent to anticipate the consequences of its actions, see Holland's "Echoing Emergence." pp. 309-342, in Cowen et al. (Eds.) (1994. op. cit. for Gell-Mann).
7. "Schemata" is the formal plural of schema.
8. See (Alberts, Garstka & Stein 2000), for a useful, recent explication of the important distinctions between the informational, cognitive and physical domains in C2 research.
9. There is new evidence for the workings of internalized map schema in human behavior. Norwegian scientists have recently uncovered evidence for the existence of grid cells in the human brain which are responsible for creating mental maps of the environment. See Hafting, T. et al. (2005); and Leutgeb, S. et al. (2005).

outputs and common feedback afforded by the shared schema of the CAS all contribute to the self-similarity of the agents composing the CAS and should improve its effectiveness and adaptability. Thus, other things being equal, just as at the individual agent level, greater situational awareness in the observation phase on behalf of the team should lead to more effective combat action for the CAS; and greater planning quality exhibited by the team in the orientation phase should also lead to greater combat effectiveness for the CAS as a whole. For example, the UDOP schema should mainly aid the team's shared mental model of the battlespace, viz. situational awareness; shared whiteboard schema should mainly aid the team's collaborative planning and replanning activities in the battlespace; and access to distributed intelligence databases contributes to both sets of processes. In sum, a broader and deeper sharing of the informational schema used by the warfighting team in the team decision-making process should lead to more widely shared quality mental models, or organized knowledge structures, which, in turn, should lead to greater combat effectiveness and adaptability for the team as a whole. In the process a new property of the CAS, shared situational awareness, should emerge and grow and contribute to the team's combat effectiveness and adaptability.

Shared mental models afford a mechanism to the warfighting team enabling effective, agile operations in the battlespace. According to Rouse and Morris (1986, 360), a mental model is a "mechanism whereby humans generate descriptions of system's purpose and forms, explanations of system functioning and observed system states, and predictions of future systems states." Here we are dealing with mental models of the battlespace as a dynamic system. Shared mental models are important to combat team decision making since "team decision making requires coordination of activity, adaptability, flexibility and anticipation of other members' behavior and…often occurs in dynamic ambiguous environments" (Cannon-Bowers et al. 1993, 236). As the authors point out, since mutual expectations are important to team performance in a wide variety of situations, holding shared general models, of the task and the team, is important.

However, shared mental models are not the sole source of mutual expectations in the Combat CAS: the self- similarity of the agents with respect to the CAS due to their self-consciously sharing common inputs, a common schematic representation of the battlespace, common planned outputs, and common feedback of results is also a major additional source contributing to more accurate mutual expectations for team members. This, in turn, should make for more effective and adaptable warfighting teams.

Internalized schema, or mental models, have generally proved useful to effective human action. Klein, for example, has demonstrated that schematic representations of prototypical situations are often directly associated with scripts that produce single step retrieval of actions from human memory, thus prompting rapid "recognition-primed decisionmaking" (Klein & Salas 2001). A similar approach has been adopted by Moffat (2007) in his Rapid Planning process model for human decisionmaking by military commanders. At the team level, Needalman, Mikaelian, Entin, and Tenny have demonstrated experimentally that military teams employing contingency plans, or multi-option plans in which different situations are linked to different planned action sequences, generally perform more effectively in combat than teams employing single-thread plans (Needalman et al. 1988).

Some classes of mental models appear better suited to combat decisionmaking than others. A mental model, or internalized schema, is a symbolic representation which may take one of two basic forms, linguistic representations and discourse models (For linguistic models, see Chomsky 1962). Discourse models make explicit the structure not of sentences but of situations as we perceive or imagine them (Johnson-Laird 1983, p. 419). Indeed pure linguistic representations do not say anything about how words relate to the world; whereas a discourse mental model, or "picture" model in the conception of Wittgenstein (1922), represents the reference of discourse, i.e. the situation that the discourse describes. The COP, for example, provides such a "picture" model that should be an aid to a team's sharing accurate discourse models of the battlespace (Hiniker 1998). Whereas there may be many different discourse models available in a warfighting team, for a given individual at a given point in time his "Situation Awareness" reflects the current state of his mental model of the situation (Endsley 2000, 12). Endsley, working primarily with fighter pilots and air traffic controllers, has demonstrated that better "situation awareness" is "probabilistically linked" to better performance (See also Hiniker & Entin 1990; also see Perry et al. 2004). The magnitude of shared situational awareness, among members of a warfighting team, is indicated by the proportion of overlap between the team members on the warfighting platforms each deems critical to the current situation.[10] In short, mental models of the current situation in the battlespace and internalized goals for the future situation, e.g. "commander's intent" or team mission or more specifically current team plan, help select what information from the welter in the environment is attended to and thereby help increase the likelihood of better decisions and better performance of action. As an aid to quality shared mental models of the battlespace, schema expressed in the form of discourse models would seem to provide the most suitable schema for the team of warfighters.

Bounded Rationality of CAS Agents

Since the informational schema, when internalized, are shared as mental models by human warfighters, their effectiveness is, of course, subject to the human cognitive constraints of bounded rationality, analogous to the effects of channel capacity constraints on the speed of information transmission over a network. Performance impairing information overload can and does occur at both the cognitive and the informational levels of a socio-technical system. It has been demonstrated experimentally in a militarily relevant context that human beings have an information load crash threshold, expressible in terms of amount of workload per minute, beyond which perfor-

10. See Appendix for measurement definitions of the key variables used here.

mance drops precipitously (Levis et al. 1987; Hiniker 2002). Finally, at the "ground truth" level of the physical world, as well, human actors, sensors, weapons platforms, communications networks, and associated software and data bases can and do become impaired in the course of warfare (see Figure 3).

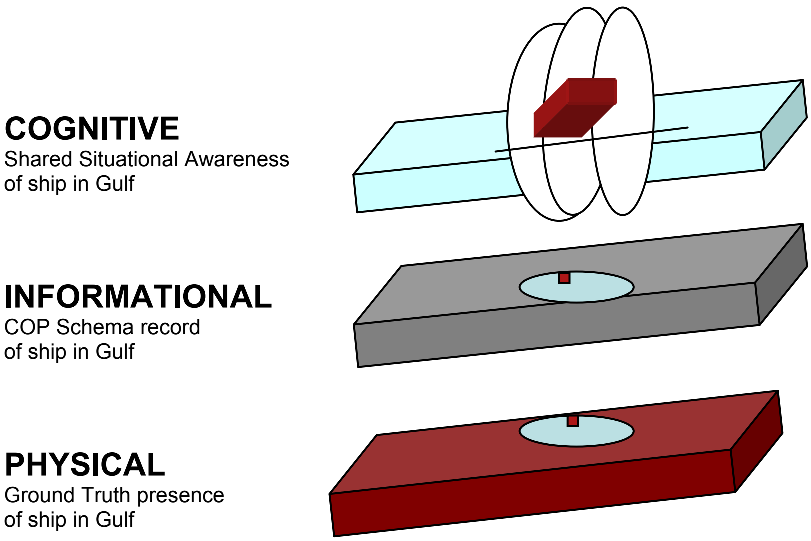

Figure 3. Three viewpoints on elements in the battlespace.

Thus the interactions of the schema-sharing CAS with its environment entail both simple linear and complex non-linear relationships. Human information overload is an instance of a non-linear relationship in that a small positive change in informational workload near the cognitive crash threshold results in a very large degradation in performance. Furthermore, new incoming information to a human actor is not necessarily automatically believed and internalized as part of the mental model; if the new information is dissonant with current belief it may be dismissed, denigrated or otherwise modified (Festinger 1957). Finally, most network interactions involving humans are not simple random network interactions; rather they usually involve "small world" nets including shortcuts or "scale free" nets including hubs and may, under certain conditions, exhibit non-linear "percolation effects" (Moffat and Atkinson 2005). Here the focus will be upon the existence, rather than the form, of causal relationships between a warfighting team's use of shared informational schema, contributing to their shared mental models, and the consequent effectiveness of their operations in the battle space (see Pearl 2001).

Some Determinants of Combat Effectiveness of the CAS

In viewing the overall effectiveness of the combat CAS, equipped with increasingly more encompassing levels of shared schema of the battlespace and increasingly common stages of the shared decision-making process, it is useful to conduct a thought experiment by conceptually removing the shared schema, common decision processes and shared mental models that augment its self-similarity from the group and then considering the consequences for concerted team action across a wide variety of changing adversary posed situations. The complete CAS is composed of agents who share a communications network, multiple sensor feeds and informational schema, consisting of common inputs, an up-to-date common picture of the battlespace, concerted team action outputs and common feedback of results; the agents also share, in some measure, mental models of the situation, of the current plan and of the team mission in accord with the high level commander's intent.[11]

11. In citing the aspects of the CAS and its agents qualifying it for self-similarity, it should be explicitly noted that the self- similarity of the CAS to its agents in the command decisionmaking area is considered to be within the informational and cognitive/psychological levels or domains only. These domains have been abstracted out for our examinations. This self-similarity is not considered to extend to the weaponry or other material assets possessed by the agents, which may vary considerably, and especially in joint operations. In the controlled experiments reported later in the paper, weaponry is always held constant across experimental treatment conditions. Nevertheless, the self-similarity of the CAS

How well would a de-scoped, multi agent system or distributed combat "team" fare when compared with such a CAS composed of agents where the CAS as a whole is highly self-similar to the agents? Suppose there were no shared sensor information between agents, no common maps, no common picture of the battlespace displaying the locations of attendant warfighting platforms; suppose no shared communications network; suppose no collaborative sharing of graphic battle plans and future schedules; no shared feedback of results in the context of common plans; suppose no rapid sensor information updates for the common input; suppose the OODA Loop processes of the several team members or agents were out of phase with each other. Now suppose the team were organized, but organized into a fixed hierarchy with only special partial views of the situation and special partial pre-assigned roles, or mission subtasks, for each of the members to perform in combat action. In the extreme this destroys, by partitioning out generally relevant information, shared situational awareness and shared plan view and also effectively eliminates shared common feedback of common results. It would seem to make the team less adaptable. At a minimum it introduces possibilities of bottlenecks under conditions of high information load. It clearly makes the "team" vulnerable to decapitation in a way that the self-similar CAS is not vulnerable.

Some Experimental Tests of the Behavior of the Combat CAS

Controlled laboratory experimentation can shed more light on the actual causal mechanisms underlying the behavior of the combat CAS. Thus the negative consequences of a rigid hierarchical or highly centralized organization are well demonstrated in the original series of laboratory experiments on communications patterns in task

to its agents in the informational and cognitive domains is an important general property that shows strong signs of impacting combat effectiveness.

oriented groups initiated by Bavelas (1950)[12]. The common experimental procedure is to create in the laboratory groups of 3-5 people, to assign them a group task and to establish certain patterns of permissible communications among them while they are working on the task (Bavelas 1950; Cartwright 1960; Guetzkow 1960). The task is typically an intellectual problem which requires that the information initially distributed among the members be collected into one place and processed to provide an answer to the problem. Then a new problem is given, and the group repeats the process several times.

The structure of the communications network linking the team members is important to team performance. Generally the experimental findings show that for simple, routine tasks centralized communications networks, e.g. a strict hierarchy, enable better performance than more decentralized structures, e.g. a circle or an all-channel pattern; but decentralized networks enable more effective group performance for complex tasks (see Bavelas 1950; Cartwright 1960; see also Hiniker and Vattikuti 1993). Decentralized networks apparently achieve this greater facility in providing faster and more accurate solutions to complex problems by affording the group members a freer hand in establishing an effective work organization. Such decentralized structures also permit the expression of a broader range of opinion to permeate the group. Morale is also affected by the group communications structure, with the incumbents of the top or central position in a hierarchy having higher morale than other members, but the average member having lower morale in such centralized structures and higher morale in decentralized structures.

12. See Alex Bavelas "Communications Patterns in Task-Oriented Groups," *Journal of the Acoustical Society of America*, 1950, 22, 725-730. This seminal article is reprinted in Dorwin Cartwright "The Structural Properties of Groups," in Dorwin Cartwright and Alvin Zander (Ed.) *Group Dynamics: Research and Theory*. Evanston IL: Row Peterson & Co., 1960, pp. 641-682. See also subsequent works by Leavitt and by Guetzkow; more recently Reiner Huber and his associates (Huber et. al. 2007) have conducted related studies with one treated here.

Thus, a decentralized network, preferably an all-channel net which is akin to a "face to face" group for a distributed team, is best suited to the combat CAS which typically confronts complex problems.

Similar controlled laboratory experiments have more recently been conducted on the sharing of information technology designed to improve combat effectiveness by groups of distributed warfighters. These controlled experiments clearly show the benefits of sharing broader levels of informational schema of the battlespace across teammates (Hiniker and Entin 1990; Hiniker and Entin 1992 A; Hiniker and Entin 1992 B; Hiniker and Entin 2006; see also Huber et al. 2007). The common experimental procedure here is to create in the laboratory groups of 3-4 distributed military officers, to assign them a group task and to provide them with one of two sets of information technology, a baseline set or an advanced technology set, to use while they are working on the task. The task is typically a warfighting mission which requires that members of the blue team, by moving or otherwise using their digital avatars, identify and prosecute a set of (red) adversaries, who are bent on capturing or destroying blue assets, while losing as few blue or neutral assets as possible in the process. The role of the adversary is played by the operator of the wargame simulator[13] which provides the combat setting as well as shooting adjudication and scoring during the combat scenario, which typically takes 1-3 hours. Performance measures are systematically taken throughout the scenario trials, usually at three equal time intervals. Then a new, modified problem scenario is given; and the team repeats the process several times, with the baseline technology or the advanced technology.

13. Several wargame simulators have been used as a part of this HITL experimental paradigm with the participation of joint warfighters including the Navy's RESA, the Army's JANUS, and the joint services' JTLS. For constructive simulations, the author has employed the joint services' JWARS (see Hiniker 2002; see also TTCP 2006).

The concept of operations used by the teams of warfighters with the new technologies during the scenarios throughout these experiments has been in accord with what is now called "edge organization" in that command or decision rights are relatively decentralized, team member interactions are relatively unconstrained, and information is broadly distributed (Alberts et al 2000; see also Hiniker and Vattikuti 1993). In the experiments cited above, except for the local tactical picture control trials, the warfighting operations of the teams were not controlled from above; rather the team members organized themselves by collaborating with each other to conduct effective operations versus the maneuvering red adversaries. Generally these experiments have found that use of a shared COP of the battlespace enables superior performance for the blue warfighting team over and above that achieved during their use of Local Tactical Picture baseline technology. The question posed was, would teams using a cross-echelon shared COP fed by both organic sensors and national sensors perform better in combat than a control team with the high commander using only a national sensor fed big picture and a pair of subordinate ship captains using only local tactical pictures fed by their organic ship sensors (Hiniker & Entin 1990, 220; Hiniker & Entin 1992 A; and Hiniker & Entin 1992 B). The second and the third of these experiments, all of which were air/sea combat scenarios set in the Persian Gulf, found that the shared COP enabled significantly increased combat effectiveness by the warfighting team, with the ratio of red losses to red plus blue plus neutral losses being significantly greater when the blue teams employed the COP (see also TTCP 2006; see Figure 4). The first experiment, the original COP prototype experiment (Hiniker & Entin 1990), found that when using the COP the blue teams displayed significantly greater situational awareness, in terms of the proportion of the mission relevant set of warfighting platforms they were able to identify correctly. The same study also found that the warfighters felt that the COP provided significantly "easier information seeking, quicker understanding, and easier communication about the situation," indicative of greater shared situation awareness among the team, than was the case when the team was using the local tactical pictures.

A recent experiment with warfighters examined a similar question regarding the performance impact of use of an individual battlefield picture versus a common battlefield picture by members of an intelligence cell in a brief simulated military operation (Huber et al. 2007). The study employed 130 four-man distributed teams composed of male and female cadets and junior officers of the German Bundeswehr, each tasked to locate and designate targets distributed over a simplified terrain grid in a simulated military operation. Each randomly composed team was given some practice with the brief (5-15 minute) game and then played it twice, first with a shared Common Results Picture (CRP) and second with an Individual Results Picture (IRP). Besides the many intriguing findings on personality characteristics of the warfighters, the significant results which are germane to this study clearly show that the teams performed more than twice as well with CRP than they did with IRP; and furthermore, they exhibited nearly 20 percent better shared situational awareness when using CRP, despite the possible learning effect advantage that would accrue to the IRP since it was always used second. Analogous to our earlier experiments comparing team combat performance with Local Tactical Picture to their performance with the Common Operational Picture in longer simulated combat scenarios, the authors state that "In contrast to an IRP, a CRP allows each team player to see immediately the search results of team mates on his/her individual screen. In the final round, each player is tasked to select all (grid) cells in which he/she suspects targets to be located based on the info available to him/her" (Huber et al. 2007, 125). Thus even with the intelligence sub-task for a combat team we have additional supportive experimental evidence showing that sharing a broader picture of the "battlespace" composed from the results of "several sensors" is superior to use of a picture composed from individual "organic" sensors only. And, as with our replicated experimental results on the COP above, the Common Results Picture provided both significantly better task performance, albeit of an intelligence subtask, and better "shared situational awareness," measured here as the degree of team consensus on the true (cell) location of the target.

Another recent experiment set in a simulated combat environment investigated the impact of a warfighting team's use of an even higher level of shared schema, the collaborative UDOP (or Collaborative COP). The collaborative UDOP allows the individual warfighter to tailor the dynamic COP map and actively collaborate over the map via drawings, markings, and annotations that instantly appear on all team mates' maps; this shared map planning functionality specifically enables the team to consider a discourse model of future plans on the map. This experiment was similar to the earlier experiments comparing LTP and COP with respect to scenarios used, viz. air/sea combat scenarios set in the Persian Gulf, standard metrics taken, and joint warfighter teams participating, but the technology comparison was different. Now the teams of warfighters used the collaborative UDOP (or CCOP) compared with a baseline COP treatment condition, used earlier as advanced technology (Hiniker & Entin 2006). The results showed significantly improved situational awareness, shared situational awareness, planning quality and combat effectiveness in most time phases of the Persian Gulf crisis scenarios when the blue teams were employing the collaborative UDOP (CCOP) in comparison to their performance using the standard COP as a baseline (see Figure 4).

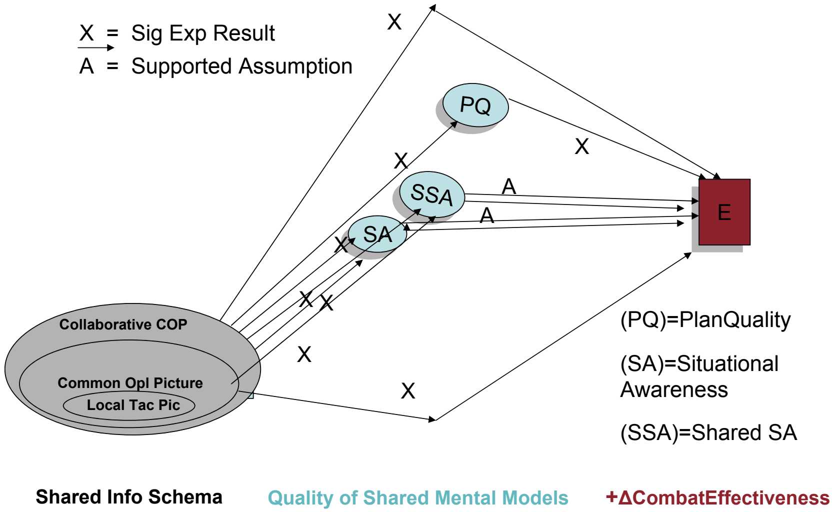

Figure 4. The role of shared schema in impacting combat effectiveness of a warfighting team via improved shared mental models of the battlespace: experimental results.

Figure 4 summarizes the significant regularities uncovered in the several controlled experiments, referred to in the text, on the cumulative improvements in situational awareness, shared situation awareness, plan quality and combat effectiveness due to use of better, more encompassing levels of shared schema of the battlespace by the warfighting teams, as the teams move from use of local tactical pictures, to use of a common operational picture to use of a collaborative common operational picture.[14] Presented in

14. The conduct of these controlled HITL experiments all made use of a within-subjects design and counterbalanced the order of presentation of treatment conditions and scenario mods. Then the analysis of the results of hypothesis testing in these experiments utilized the within-subjects Analysis of Variance (ANOVA) procedures to determine whether or not use of the new information technology or schema enabled the warfighting teams to perform significantly more effectively on the NCW performance metrics examined when compared to their use of the baseline technologies. The general criterion of statistical significance used in Figure 4 is $p \leq .05$; the interested reader is referred to the published individual experiments cited in the text for more details on the particular

this manner, Figure 4 depicts a provisional causal model with the arrows indicating the direct causal linkages uncovered in the experiments between the broadened level of shared informational schema used by the warfighting teams, the consequent increased quality of shared mental models of the battlespace achieved by the members of each, and the subsequent improved effectiveness of the teams in the simulated combat operations versus the red adversary. Combined with some reasonable assumptions and correlational evidence linking the quality of the shared mental models to the resulting improved combat effectiveness achieved, specifically for situational awareness and shared situational awareness, these empirical findings provide substantial support for the view of the effective combat CAS presented in the first part of this paper. These findings at the group level are consistent with yet transcend the conventional observations at the individual level. At the individual level it is commonly observed that improved situational awareness and improved plans yield improved combat effectiveness. Beginning with the COP / Local Tactical Picture comparison, the warfighting team experiments show that increasing the degree of self-similarity of the CAS by providing all agents a common input in the form of shared COP schema screen input, versus the variable visual inputs provided by the different LTP inputs to the different agents, leads to significantly increased situational awareness by the teams, increased shared situational awareness (as claimed by team members in post-experiment questionnaires), and increased bottom-line combat effectiveness for the teams as a whole (Hiniker & Entin 1990; Hiniker & Entin 1992 A; Hiniker & Entin 1992 B). The later experiment, which takes the COP as baseline for comparison, further increases the self-similarity of the CAS by providing a shared Collaborative COP (or UDOP)

methods employed. Use of the standard quantitative performance metrics also permits one to estimate the values of the NCW parameters exhibited by the warfighting teams, under each of the treatment conditions (see Appendix). In addition to these objective performance measures, subjective evaluations by the warfighters on the relative merits of the advanced and the baseline technologies were solicited, analyzed and incorporated into the engineering of the evolving technologies.

schema, which provides the new capability to draw possible future situations on the shared COP display, and successfully enabled the development of an improved shared common plan of action output (PQ) by the teams while effectively providing common feedback of results of plan enactment on the team's shared COP display. Team use of this Collaborative COP ensemble resulted in further significant increases, beyond the COP baseline, in situational awareness, shared situational awareness and combat effectiveness for the team as a whole, especially for the scenario phases entailing a surprise attack initiated by the commander of the red team, requiring agile replanning by the blue team (Hiniker & Entin 2006)[15]. In sum, the CCOP technology shows the best promise so far examined for constructing an effective Unified Net-Enabled Team (UNET).

Whereas the direct arrow, X, links in Figure 4 show statistically significant relations of causal independent variables directly manipulated as treatment conditions in the experimental designs, the arrow "A" links are not the result of direct experimental manipulation, but are more weakly inferred causal links due to the correlational association observed between situational awareness and combat effectiveness, and between shared situational awareness and combat effectiveness in several of the experiments reviewed here. While most of the experiments directly manipulated the information technology or schema, as the independent variable, one early experiment directly manipulated planning quality and demonstrated a causal linkage between the planning quality displayed by the warfighting team and

15. It is noteworthy that the only significant finding uncovered that favored the baseline COP condition occurred for combat Effectiveness during time phase one of the three time phase scenarios, with the last two phases involving replanning due to a surprising new attack by red resulting in significantly greater combat Effectiveness for the collaborative UDOP treatment condition. We surmise that the greater familiarity of the warfighters with the baseline COP technology and conops contributed to their initially better performance in phase one of the three phase scenarios, but dampened their agility in replanning during phases two and three (see Hiniker & Entin 2006).

consequent combat effectiveness (Needalman et al 1988)[16]. Thus the two stage mechanism of using the collaborative COP to increase planning quality and having the increased planning quality result in increased combat effectiveness is a two stage causal mechanism that is better supported by our experimental data.

Concomitant with the increasingly broadened shared schema manipulated as independent variables in these experiments with warfighting teams is the increasing self-similarity of the decisionmaking processes of the component Agents of the CAS. This property of the CAS and its Agents appears to be quite powerful in linking shared situational awareness to the increased combat effectiveness and agility exhibited by the warfighting teams examined.

Way Ahead

The significant results of the controlled experiments examined here provide considerable support for the view that when a distributed warfighting team, fully linked by a broad all-channel network, is confronted by rapidly changing situations posed by an adversary, it is better able to adapt effectively when the members are highly self-similar to the team as a whole by virtue of sharing common decision inputs, planned outputs and feedback of results on a common schema of the battlespace. The team members then constitute agents of a combat Complex Adaptive System and are also well described as composing a Unified Net Enabled Team. Such an arrangement of humans and technology enables up-to-date shared situational awareness and rapid replanning and self-synchronization of actions by team members, not enjoyed by simpler multi-agent systems which do not share such information technology across the

16. Note that planning quality (PQ) is not a variable that was formally measured as a dependent variable in any of the early COP experiments conducted in the 1990s; hence we cannot strictly infer that no causal relationship exists between COP use and improved planning for the COP / LTP comparison which is a possibility in Figure 4 considered as a causal diagram (see Pearl 2001).

distributed agents. One conducive psychological mechanism for such an agile warfighting team employing such technology seems to be the development of more accurate mutual expectations among team members regarding the actions of the adversary and the team members, themselves, in the rapidly changing battlespace. Although we have much empirical support for the above view, further investigations, especially controlled experimentation, could help pin down the mechanisms involved in this intriguing phenomenon and sharpen the view provided by the evidence assembled so far.

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Appendix

Measurement Definitions for Dependent Variables in COP Experiments

Situational Awareness (SA) = Proportion of mission critical set of warfighting platforms in the battlespace correctly identified by a warfighter (Ground Truth cf. warfighter's Cognitive Operational Graphic (COG) @ t_i).

Shared Situational Awareness (SSA) = Proportion of overlap between pairs of COGs for complete warfighting team.

Plan Quality (PQ) = Accuracy of knowledge of scheduled sequence of blue moves (Five item Likert scale planning process evaluation scoring method used in Hiniker & Entin 2006).

Speed of Command ($\mathbf{t_d}$ = t_c + t_r +t_a + t_b), where total speed of command is the sum of time to size up situation + time to plan + time to act + time to complete decision cycle with battle damage assessment.

Combat Effectiveness (E) = Loss/Exchange Ratio = red platform losses / (red + blue + neutral losses).

Agility (AG) = Ability of a warfighting team to maintain Combat Effectiveness by rapidly recognizing and reacting to a changed situation posed by a red adversary.

Subjective Opinion of Operational Value of Technology = Participants' scoring of value of the technology on seven point Likert scale.

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