A Model Of Command And Control Processes For JWARS: Test Results From Controlled Experiments And Simulation Runs

Paul J. Hiniker, Ph.D.

Defense Information Systems Agency
Technical Integration Services Directorate
5275 Leesburg Pike
Falls Church, VA 22041

(703) 882-1785

hinikerp@ncr.disa.mil

ABSTRACT

The purpose of this paper is to provide a basic model to aid assessment of the effects of changes in C2 on combat outcomes in JWARS. We lay out essential elements of a general Complex Adaptive System (CAS) model of C2 processes, develop measures of C2 performance and combat behavior, and derive some hypotheses on C2 effects on combat outcomes. C2 processes have a multiplicative effect with weaponry on combat outcome; combat decision loop speed and information superiority over the adversary increase combat performance; increased information load on decision makers and narrowed communications channels limit combat performance. Net Centric Warfare practices lift these limits and permit aggregated teams to fight in speedy synchronicity increasing combat performance. These hypotheses are tested against evidence from four controlled experiments, three military exercises, and hundreds of simulation runs of stochastic combat models.

INTRODUCTION

JWARS (Joint Warfare System) is a constructive, event-stepped simulation system that describes the behavior and interaction of military forces, composed of Battle Space Elements, across the joint warfighting spectrum. JWARS has several important characteristics: an explicit three dimensional battlespace, sensitivity to the effects of terrain and weather, logistically constrained force performance, explicit representation of key information flows, and perception-based command and control (C2) (Maxwell, 2000). In JWARS each Battle Space Element has organic C2 capability and its action is largely based on perceived truth. The information flows in JWARS

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C2 can be visualized employing the OODA loop paradigm shown in Figure 1 below. The question naturally arises as to how well this C2 structure in JWARS conforms to the empirical regularities believed to exist in the human use of real world C2 systems.

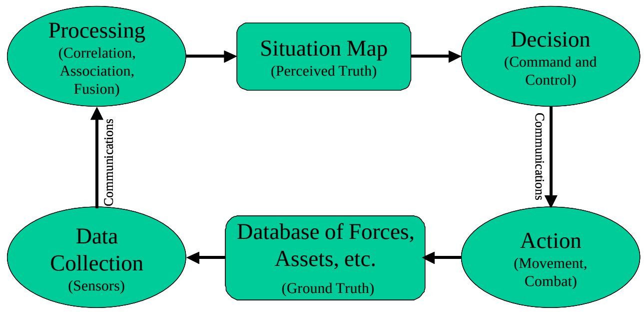
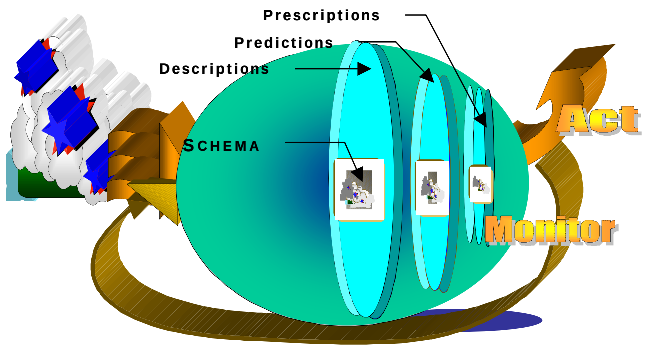


Figure 1. JWARS Logical Structure (based on C2)

1 ELEMENTS OF THE CAS MODEL

The basic elements of the general CAS model are military commanders with communications facilities, sensors, and weapons on platforms located in space and time who are engaged in conflict with similarly outfitted opposing commanders (Hiniker, 2001). The communications facilities



have varying levels of connectedness, information loading, and time lags. The sensors have varying ranges and probabilities of detection. The weapons on platforms have varying speeds, ranges, and probabilities of kill. Any object in the conflict can be moved, sensed, or shot. The commanders' general mission objectives are to maximize sensing and destruction of opposing forces while minimizing the same to own forces.

During a conflict scenario, a commander receives a stream of information about himself and his environment, identifies particular regularities, and compresses them into concise schema as depicted in Figure 2.

Figure 2. Complex Adaptive System (CAS) with Schema.

With further information from the stream, he can supply relatively accurate descriptions and reliable predictions about his environment as well as prescriptions for favorable actions. The results of these actions are then fed back to the commander. The foregoing comprises the essential command decision cycle. (Lawson, C2 ’78; Wohl, SHOR ’81, Hayes et al; HEAT 1982; Hiniker; HEAT Exp Method 1991; Gell-Mann, CAS 1992).

Thus the command decision cycle involves inputs from the environment, situation assessment, course of action choice (planning) with prediction, action, and feedback of results, an essential element of the control process. All are necessary phases of a more or less time consuming command decision sequence for a complex adaptive system; removal or degradation of the operation of any phase of the general process will result in impairment of the effective operation of command and control of the system. (Hayes, Strack, et al, HEAT (Headquarters Effectiveness Assessment Tool) Model 1982; Boyd, OODA Loop (Observe Orient Decide Act), 1987; Serfaty, Entin &Tenny, HEAT, 1988).

In the decision process, the commander does not attend to all information from the environment but utilizes schema to sort through and summarize the most relevant information for his action decision. Indeed, the amount of information a commander can process per unit time is limited. A major function of the commander is the reduction of two types of uncertainty: uncertainties regarding the location of own and enemy forces in the environment and uncertainties regarding the battlefield outcomes of hypothetical courses of action. The commander’s assessment of the situation and action decision serves to reduce the overall magnitude of these uncertainties. Critical information for the commander’s move, sense, shoot, or stay action decision is the time wise location of own and enemy forces. Such critical information has historically been posted to paper battle map schema and currently is posted to rapidly updated and shared electronic battlefield map schema such as the more highly evolved and complex GCCS Common Operational Picture (COP) (Hiniker & Entin, Exp 1990, 1992a, 1992b; Hiniker, 1998). In JWARS, the COP is called the JEF (JWARS Equipment and Forces).

The COP possesses all the general characteristics of a Schema for a CAS (Martin, 1994; Hiniker, 1998). As with any complex adaptive system, the COP affords the commander in a military command center with a useful schema for combat in the same way that Maxwell’s equations afford the physicist a useful, albeit more powerful, schema to deal with electromagnetic phenomena. In general, a schema is an internal representation of summary aspects of the external environment. The COP shares the essential characteristics of a schema. The COP *summarizes* important information about the battlefield environment; it *internalizes* information from the environment by representing it within the command center; it *assimilates* states of the battlefield environment into a consistent framework, providing current values for battlefield variables; and it *accommodates* to radically new kinds of information in the environment by evolving to new forms under strong adaptive pressures. The COP is *inclusive*, potentially representing any relevant state of the environment by zooming to several levels of detail; it is *diagnostic*, conveying information about history that can be useful to predict the future, as with platform movement vectors; and it is *recursive*, embedding within itself subordinate schema such as the algorithms automating platform placement from radar tracks. Thus the COP constitutes an informational schema for the CAS which mediates between the complex physical events occurring in the battlefield environment and the battlefield commander’s perception of the same.

Just as the COP map schema serves to reduce the commander’s uncertainties regarding accurate description of the situation in the battlefield environment, other schema serve to reduce the commander’s uncertainties regarding the hypothetical preferred course of action: wargame simulators enable the commander to "what if" his various options with relatively reliable predictions of the likely battlefield outcomes of his alternative courses of action. Taken together, COP map schema and wargame simulation schema go a long way toward reducing the total uncertainties facing the battlefield commander in the command and control of his forces.

A commander does not act in isolation. By definition, a commander exercises authority over subordinates and can order them to move, sense, shoot or stay. Furthermore, command implies the existence of a communications link between commander and subordinate. Thus the critical communications capability for the commander is the ability to transmit move, sense, shoot or stay orders to his subordinates, while being apprised of sensor reports on all relevant platforms, and the capability to receive feedback of results. Taken together, a combination of commander and subordinate commanders comprises a larger, more complex, and more capable superordinate CAS containing nested CASs linked by authority relations and communications while sharing, in some measure, the same sensors, schema, and weapons.

2 C2 MEASURES OF PERFORMANCE

There are several measures defined on the C2 processes that relate to their impact on combat outcomes.

- Congruity (C) between Commander's Assessment of the Situation and Ground Truth. When ground truth is conceived of as the true location of all own and enemy weapons and sensors in the battlespace, the degree of situation assessment incongruity is the percent of all relevant elements that are incorrectly identified in the commander's perception. If the commander's perception is identical to the COP schema, this incongruity can be measured in terms of the percent of incongruent elements between the two pictures, the COP and ground truth. If not, the incongruity can be measured directly between the commander's perceptual sketch and ground truth (Hiniker and Entin, 1990). This Congruity concept provides a measure of what is often called Situation Awareness. Errors contributing to incongruity are of two kinds, false positives and, more frequently, false negatives which are often due to incomplete monitoring of the battle space by sensors or to missing or time lagged communication of critical sensor information to the COP information fusion location. Strictly speaking congruity of an element with ground truth entails target quality location of the entity, correct classification of the type of entity, and correct identification of the allegiance of the entity.

- Reliability of Commander's Forecast of Combat Outcome (R). In choosing a course of action or plan, the commander can be more of less reliable in his prediction of own force losses that he expects to incur. This reliability can be measured by taking the commander's predicted losses as a percent of actual (Ground Truth) losses, and normalizing the scores such that $0 \leq R \leq 1.00$.

- Speed of Action (t_A). Once the commander has decided upon a course of action, how long does it take him to put it into effect? Such action implementation requires communication links, with possible time lags, to those who would implement the action.

- Speed of Feedback (t_B). Once the commander has issued an order to act and had it implemented, how long does it take him to receive report of the results? Results of shoot orders, for example, are critical to issues in retargeting and such results must be relayed over possibly time lagged communication links.

- Decision Cycle Time (t_D). Total Decision cycle time is the sum of the sequenced time phases composed of time for Congruent situation assessment, Reliable course of action forecasting, Action itself, and feedback of results.

$$t_D = t_C + t_R + t_A + t_B \qquad (1)$$

All are measured in minutes. In general, the greater the communication induced time lags in conveying the critical information for these four essential processes, the greater the total decision cycle time.

- Capacity of Communications (M). For commanders to communicate move, sense, or shoot action orders and to receive updates on positions of relevant battlefield platforms, communications links must exist between and among teammates and sensors. Faulty communications in the net may contribute to longer decision cycle times as a result of communications lags; networks may vary in topology and may contain bottlenecks. Besides minimal required connectedness for the spread of critical information, networks must not become overloaded by the volume of information carried.

- Sensor Coverage (I). For the COP to have complete coverage of all relevant battlespace platforms, especially all red weapons platforms and sensors, their types and locations, with sufficient accuracy for targeting, these platforms must be sensed by blue sensors and the information transmitted to COP fusion locations in timely fashion. Such sensors can also vary on geographic coverage of the battlespace, with gaps guaranteeing that extant platforms go undetected.

- Command Team Consensus on Situation Assessment (N_s). For certain types of combat operations, especially Net Centric Warfare, it is important for commanders and subordinates to share a common view of the situation. This team commonality can be measured pair wise with a common elements measure, but now between the commander’s perception of the battle space and the subordinate’s perception of the same, across all team members. This commonality or overlap measure of Shared Situation Awareness has been demonstrated to be promoted by a shared picture of the battlespace displaying pooled sensor reports (Perla, 2000).

- Command Team Consensus on the Plan (N_p). For certain types of combat operations it is also important that commander and subordinate share a common plan, where plan is defined as a scheduled sequence of blue moves. Atop the plan is the Commander’s Intent which includes the overarching goals for the operation. The commonality of this position/situation timeline can be measured in similar fashion to Situation Consensus, by counting common elements.

- Quality of Schema (S). Schema serve two major functions for the CAS. The more complete and accurate the description of the battlespace by the COP schema and the more predictive the conditionally forecasted battlefield outcome of the COA by the model/simulator, the greater the quality of the CAS Schema.

3 COMBAT AND BACKGROUND VARIABLES

The exercise of effective command and control over military forces requires not only accurate situation assessment, option evaluation, communication, action execution, and feedback of results, but also use of weaponry for combat. Warfighting scenarios can vary in scale, op tempo, pace of battle, attrition rate and exchange ratio.

- Scale of Battle. Scale of Battle is measured by the number of blue (F) and red (E) weapons platforms involved in the battle.

- Op Tempo. Op Tempo (O) is measured as the time rate of change of positions of all blue platforms.

- Pace of Battle. Pace of Battle (P) is measured as the time rate of change of positions of all platforms, red and blue, involved in the battle.

- Attrition Rate. Attrition Rate is measured from the kill rate per second per platform, $\mathbf{C}_f$ for kills by Blue forces and $\mathbf{C}_e$ for kills by Red forces.

- Battlefield Exchange Ratio. The Battlefield Exchange Ratio (X) is the conventional overall Measure of Effectiveness (MOE) applied to combat. X_f is composed of the ratio of red (enemy) losses to the sum of all losses, red plus blue (friendly).

$$X_f = \text{-delta } E \,/\, (\text{ -delta } E - \text{delta } F \,) \quad (2)$$

4 SOME HYPOTHESES AND TESTS ON C2 EFFECTS ON COMBAT OUTCOMES

Considering the foregoing model elements and variables, C2 processes can be shown to affect combat outcomes in several significant manners: as a rational force multiplier, as a provider of major tactics for achieving victory in battle, as a conveyer of chaos in combat, as a limiting factor on timely tactics in combat and as a framework for an emergent form of highly effective combat organization.

4.1 C2 Force Multiplier

C2 processes act as a multiplier on weapon systems in combat operations. In Van Trees (1988) review of the state of C3 research after a decade's work, he notes that improved C2 technology can multiply the effectiveness of a given force structure in battle. He lends credence to this proposition by pointing to the Pueblo incident in which failure to get Blue aircraft to the hostage rescue scene on time resulted in a failed operation, a force effectiveness of zero.

Nevertheless many experimental studies have also demonstrated the existence of the positive C2 multiplier. In a replication of a controlled experiment employing a sea/air battle scenario set in the Persian Gulf, Hiniker (1991) found a 26 percent improvement in average battlefield MOE (from war game simulator) for teams using shared COP schema compared to control teams with high Command JTF using national sensor fed big picture views only and a pair of ship captains using only local tactical pictures fed by their organic sensors; weaponry was constant, the same for both experimental and control teams. (X Exp =.68; red platforms lost/red plus blue platforms lost; X Controls =.54; for 16 trials, $p = .04$). Here improved C2 processes and technology were shown to cause a significant 26 percent increase in the battlefield exchange ratio for blue X_f.

In combat modeling, C2 factors, such as shared COP schema, are viewed as multipliers of the force coefficients, $\mathbf{C}_f$ and $\mathbf{C}_e$, in Lanchester equations:

$$dF/dt = -\mathbf{C}_e E \text{ and } dE/dt = -\mathbf{C}_f F \qquad (3)$$

F = friendly (Blue) force size and $\mathbf{C}_f$ = friendly kills/sec/unit.
E = enemy (Red) force size and $\mathbf{C}_e$ = enemy kills/sec/unit

4.2 Decision Superiority

The quality of a combat decision is the product of situation assessment congruity (C) and selected course of action reliability (R). Both are necessary. The effective commander accurately sizes up the situation and reliably chooses a course of action. Quality decisions rapidly made and implemented are what make the difference in combat. Indeed, Decision Superiority is a major component of the Joint Vision 2020 concept of Information Superiority in joint warfighting.

"In any conflict, the antagonist who can consistently and effectively cycle through the OODA Loop (or HEAT Cycle) faster --gains an ever-increasing advantage with each cycle" (USMC C2 Concept Paper, 1996). In other words, the commander who achieves an effective Decision cycle speed (D) greater than that of his adversary should prevail in combat, where:

$$D = 100 \text{ x } (C \text{ x } R) / \sum (t_C + t_R + t_A + t_B). \qquad (4)$$

So D represents the blue commander's measured decision loop in terms of decision quality utiles per minute. As a practical matter, the value of D would be averaged across a number of decisions.

Now consider the Lanchester attrition equations (3). Let $\mathbf{C}_f$ be composed of the product of two necessary components, c2, for C2 processes, and w, for weaponry, so $\mathbf{C}_f = c2_f \text{ x } w_f$. Assume equivalent weaponry for the opponents, $w_e E = w_f F$. Now let $c2_f = 100\ (C_f \text{ x } R_f) / t_{Df}$ as above. (N.B. Poor communications linkages would serve indirectly to degrade the several components of D). Then the Battlefield Exchange Ratio for blue, $X_f = 1 / (1 + t_{Df}\ (C_e \text{ x } R_e) / t_{De}\ (C_f \text{ x } R_f))$. Hence, the key ratio for Decision Superiority (DS_f) for blue is blue's decision quality times the latency of red's decision cycle relative to red's decision quality times the latency of blue's decision cycle:

$$DS_f = (C_f \times R_f)\, t_{De} / (C_e \times R_e)\, t_{Df}. \qquad (5)$$

Thus blue has decision superiority over red if and only if this ratio is greater than 1.00. The magnitude of blue superiority is the degree of assured decision superiority for blue. The implications of this hypothesis are testable within JWARS. There Processing, Exploitation and Dissemination (PEDs) delays from sensing and fusing through situation assessment with the updated JEF should be positively correlated with impaired combat performance, for blue and for red.

In a related controlled experiment of 12 trials, including several measured components of D, while holding weaponry constant between experimental and control groups and using an air/sea battle set in the Persian Gulf, Hiniker and Entin (1990) already have found significant correlations between use of shared COP schema and greater situation assessment accuracy, C, as measured by the perceived overlap in mission critical platforms in the commander's perceptual sketch compared with ground truth from the RESA wargame simulator. Here use of shared COP schema was shown to cause improved situation assessment accuracy, C_f. In addition to improved individual shared situation awareness, the naval officer subjects showed in post trial questionnaires that use of shared COP schema significantly ($p = .05$) improved their shared situation awareness, including easier information seeking, quicker situation understanding, and easier communication about the situation. Here use of shared COP schema was shown to cause improved shared awareness (a correlate of Ns). Finally, prima facie evidence was also found here for use of the COP as causing improvement in effectively synchronizing the actions (correlate of t_A) of the warfighting team: when measuring the time it took the warfighting teams correctly to monitor, suspect, and finally identify the true aggressor in the scenario, it was found that the teams using the COP collectively achieved this result 10 percent faster than the control teams (maximum possible score 600 minutes of time remaining; 6 COP trials averaged 356; 6 control trials averaged 321; $t = 0.35$, n.s. for one tailed test).

The experimental findings above demonstrating causal relationships between use of shared COP schema and improved situation awareness, shared awareness, synchronized actions, and combat outcomes can all be viewed within the broad framework provided by the recent Information Superiority value chain. (Alberts et al., 2001). Here we have shown that use of shared COP causes improved situation awareness, shared awareness, synchronized actions, and more favorable combat outcomes.

In an emerging theory of Net Centric Warfare linking elements in the physical, informational and cognitive domains, Garstka (2000) has defined a concept of information superiority and related it to the evidence from military exercises. Information superiority is defined there in terms of the relative information positions of battlespace entities. In our terms, ignoring the distinction between information on own and enemy force positions, this distance is simply the difference between the Congruity of the blue COP and the Congruity of the red COP. Thus, Decision Information Superiority:

$$DIS_f = C_f - C_{e.} \qquad (6)$$

Garstka then asserts that improved information position (our DIS) is associated with improved shared situational awareness (our N_s) which is associated with improved battlefield exchange ratios (our X_f), all of which are advantages of Net Centric Warfare(NCW) operations over Platform Based Warfare operations. The impressive evidence assembled by Garstka from military exercises comes first from Air Force data collected on over 12,000 sorties showing that the kill ratios for JTIDS equipped aircraft over non-JTIDS equipped adversaries were more than 250 percent greater; the JTIDS equipped aircraft shared digital information between battle platforms that improved blue information position yielding a relative information advantage over their adversaries (HQ USAF, '97). Next, the Navy Fleet Battle Experiment Delta conducted in October 1998 with a counter special operations forces operation mounted against hundreds of invading North Korean boats, while blue made extensive use of a shared COP among Army Apache helicopters, Air Force AC-130s, and Navy and Marine units, resulted in significantly increased blue combat power and mission accomplishment in half the time required by platform –centric operations (Cebrowski, 1999). Finally, in the Army's Task Force XXI advanced warfighting experiment, the improved information position established by the EXperimental FORce through use of the Tactical Internet enabled it to generate increased combat power and resulted in a six-fold increase in Op Tempo and a ten-fold increase in lethality (LaPorte and Noyes, 2000; Bond, 1998).

In our view expressed above, while both situation awareness and shared awareness are important determinants of combat outcome, neither information superiority nor its sharing, are the sole determinants of decision superiority, DS_f, or combat outcome, X_f, even when opposing forces have equivalent weaponry. In addition to relative information position, the speed of the decision loop, including time to carry out Action, is also a determinant of combat outcome. Furthermore, the reliability of the commander's forecast of combat outcome, R_f, when selecting a COA is another significant informational component of decision superiority affecting improved combat outcome and one which also goes beyond information position or "information superiority". Indeed, a recent advanced C2 study showed that teams sharing both an accurate view of the situation and a clear statement of Commander's Intent fared better in battle than those that did not (OPNAV/N6, 2001). A commander must not only size up the situation accurately, he must also know how to choose a course of action with the best consequences: the good commander needs a good COP and a good plan.

In a rigorous study of "the knowledge enhanced Lanchester" relating certain aspects of battlefield information to combat outcome (Perry et al., 2001) have found strong theoretical reasons to believe that congruity of shared COP schema should strongly influence combat outcome. Returning to the original Lanchester force equations, Perry has chosen to insert knowledge, K, as a force multiplier. K is equivalent to our congruity of the COP with ground truth, C, provided we restrict the area of consideration to blue's view of the enemy and not that of own forces; thus a perfect K_b is equivalent to perfect knowledge of the red target set by blue. Perry goes on to show that when K_b comes from organic sensors only, where blue can only fire at one target at a time, the conditions for a blue victory conform to the Lanchester Square Law:

$$\mathbf{C}_f\, k_f \,/\, \mathbf{C}_e\, k_e > (E/F)^2 \qquad (7)$$

By comparison, when K_b comes from external knowledge, e.g. from higher or adjacent headquarters or from national sensors, such that blue can fire on many targets in each time cycle, the conditions for a blue victory conform to the Lanchester Linear Law:

$$\mathbf{C}_f C_f / \mathbf{C}_e C_e > E/F \qquad (8)$$

Under the latter conditions, a much smaller initial commitment of blue forces is required for victory. Here a doubling of blue effectiveness, through enhanced knowledge of the enemy, has the effect of doubling the favorable force ratio; whereas above, a doubling of blue effectiveness has the effect of only increasing the favorable force ratio by a factor of the square root of 2.

They then report the results of hundreds of simulation runs of mixed cases where level of knowledge is systematically varied from high to low. Their simulation is a stochastic process where the maximum number of units a blue or red force can encounter during any time period is varied and the set unit effectiveness parameters are the probability that a unit is detected and the probability that a detected unit is destroyed. They consistently find that, beginning with the pure linear case, as red knowledge of blue is systematically degraded, the fraction of blue forces surviving increases monotonically and that of red steadily decreases. Perhaps the parallel processing enabled by shared COP schema provides a fundamentally different form of effective warfighting than that afforded by the serial processing associated with organic sensors.

In general, Schema quality is a partial determinant of combat outcome, and it acts indirectly both through increasing situation assessment Congruity and through increasing option evaluation Reliability to improve combat outcome, X_f, via the Quality Decision Loop. As a first approximation,

$$C_f = a_i + b_i S \text{ and } R_f = a_j + b_j S \qquad (9)$$

In developing technology for command centers, we are constructing automated schema that should be responsive to both of these key aspects of command decision making.

Information Operations (IO) may also play a significant role in determining combat outcomes. Besides efforts to increase blue's decision superiority, DS_f, by increasing blue's decision quality or loop speed, DS_f can also be increased by information operations (IO) conducted against the enemy, such as destruction of enemy sensors, communications jamming or delaying of links essential to the enemy decision loop, or information overloading of enemy decision making. Any operations which serve to disrupt enemy decision quality, D_e, including his assessment of the situation, C_e, or the reliability of his option evaluation, R_e, or lengthen the latency of the enemy decision cycle will improve DS_f and, consequently, X_f. It follows, of course, that blue may be vulnerable to similar Information Operations by red.

4.3 Information Overload

The capacity to make effective combat decisions varies across commanders but is limited for all. As the Pace of Battle (P) increases, and more red platforms appear as threats and potential targets to be processed and shot, the capability of the blue commander to exhibit high effective Decision cycle speed increases to a certain threshold value after which his decision performance crashes toward zero.

Yerkes and Dodson have established a well generalized law relating human performance to the log of workload, in bits per second. Experimenters at MIT (Casey, Louvette, Levis, exp 1987) conducted an investigation of the applicability of the Yerkes-Dodson law to an air defense problem involving rapid identification of enemy aircraft with variable interarrival times. They found strong confirmation for the operation of the Yerkes-Dodson Workload Curve and for the existence of normally distributed information overload crash thresholds, Theta.

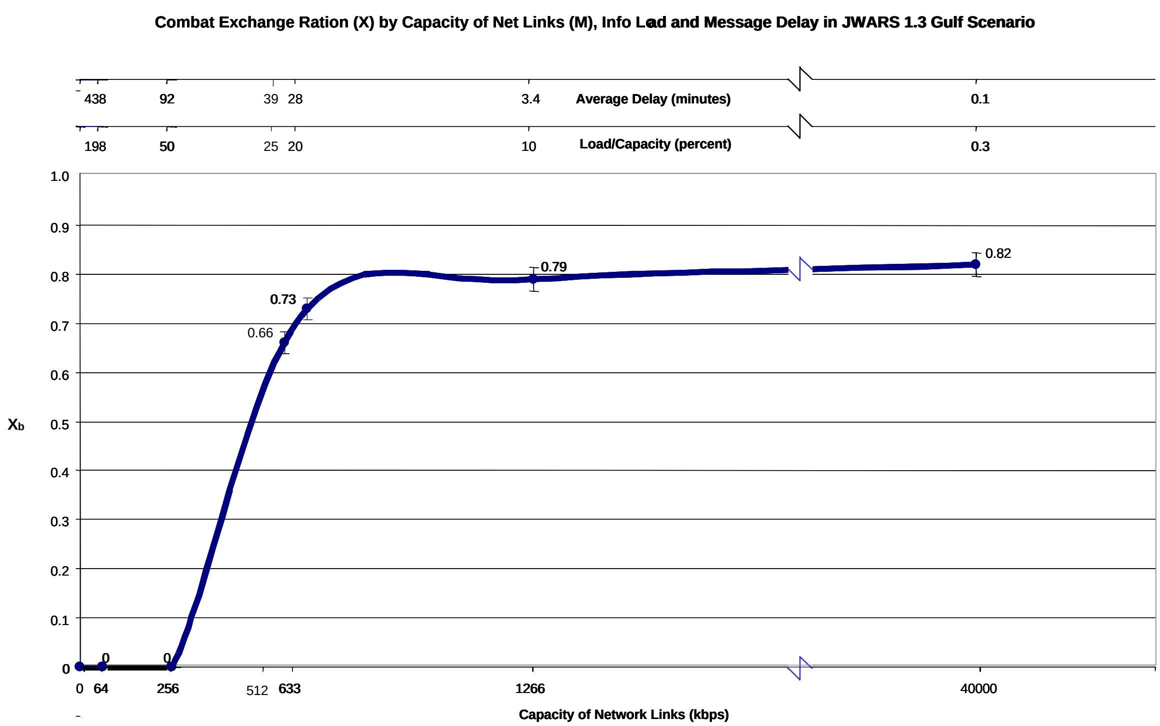
$$D = \log P, \text{ for } P \leq \text{Theta} \qquad (10)$$

Combat decision-making performance is undoubtedly a function of combat information load which depends upon the pace of battle; and there certainly exists some combat workload threshold beyond which decision-making performance crashes.

In terms of Complexity Theory, Theta is a key parameter in a region where a small change in the Pace of Battle input will result in a very large change in effective decision cycle speed output and therefore in the ensuing battlefield exchange ratio. Research on other types of CASs has shown high levels of information processing occurring in systems just below the phase change threshold and just prior to the onset of chaotic behavior. It would seem advisable for the enlightened battlefield commander to strive to operate close to Theta while avoiding exceeding "the thin red line" if at all possible.

4.4 Communications Channel Capacity

Without rapidly conveying critical combat information over communication channels (M), the commander cannot perform effectively in combat. We hypothesize that delaying the receipt of critical messages in combat by narrowing the channels of communication with respect to their load decreases combat performance. As a first approximation:



$$X_f = a + b_i M_f \qquad (11)$$

To test this plausible hypothesis within JWARS 1.3, we devised a small Persian Gulf scenario composed of 3 blue ships armed with Harpoon missiles protecting an oil platform under assault by successive waves from 12 heavily gunned red fast attack craft armed with beefed up Exocets. The link capacity of the blue communications net, which carried detection messages from ships radars to command fusion stations and shoot orders from higher command echelons to shooters, was systematically degraded from 40,000 kbps to 64 kbps with the consequent increased average time delays as shown in Figure 3. As a result of running 40 trials for each of 6 descending capacity settings, blue combat performance steadily dropped from a high of .82 to a low of .00 with a sharp decrease occurring between 633 kbps and 256 kbps using the JWARS early version 1.3 delay tables provided us.

A closer approximation of the relationship of communication channel capacity to combat outcome is provided by the logistic growth curve:

$$X_f = L / (1 + Ae^{-BM}) \qquad (12)$$

In Net Centric Warfare we expect the limiting value of blue effectiveness, L, and the growth factor, A, will be lifted above those for platform centric warfare. NCW places a premium on wideband channels of communication.

4.5 Superordinate CAS Construction

Net Centric Warfare (NCW) is a warfighting philosophy which places maximum emphasis on the C2 component of the Lanchester coefficients, as opposed to the weapons platforms component, to drive the C2 multiplier to its limit . (See Cebrowski, 1998). Consider a warfighting scenario in which the weaponry ($w_f F$) is held constant while friendly C2 processes are optimized to gain maximum advantage over the enemy. The blue commander would rapidly (min t_C) arrive at a situation assessment congruent (max C_f) with ground truth, fed by national and near real time overhead sensor reports and by sharing organic sensor reports on the COP from his confederates; he would rapidly (min t_R) develop a preferred course of action with reliably predicted (maxR_f) outcomes, perhaps in collaboration with confederates or experts using a Common Action Picture (CAP) developed on a shared whiteboard. Relying on highly connected communications (max M_f), he would rapidly enact his plan (min t_A) and receive fast (min t_B) feedback, poised for the next move. In the process, we hypothesize the commander would exhibit substantial Decision Superiority over the enemy as detailed in Equation (5).

Now consider expanding the commander in a single command center into a larger unit linking commanders in many command centers. Those commanders who share sensors, schema, weapons, and feedback and who are necessarily linked by communications (in the net) and have an accepted authority hierarchy constitute an emergent super ordinate CAS with subordinated CAS's sharing a common fate in combat. The foregoing combination of functionalities comprises a complete CAS which can fight as a single large unit or, we hypothesize disaggregate into smaller sub CASs which can organize themselves and synchronize their actions into a complete and cohesive, albeit smaller, effective CAS unit.

The forgoing super CAS requires high interaction among confederates in situation assessment, planning and COA synchronization during battle. High interaction requires robust communications links between and among CAS confederates and rapid updates of shared COP schema via communications links to the COP from organic sensors and overhead surveillance assets. This, in turn, should result in higher team consensus on situation assessment and plan. An emergent benefit arises when the super CAS is confronted with high pace of battle conditions, approaching information overload in one sector of the battle space (See Fig. 4). Since tasks can be off loaded to nearby confederate CAS members, it is insufficient for the opponent to overload a single CAS, he must overload the super CAS which, we hypothesize, has a higher effective Theta.

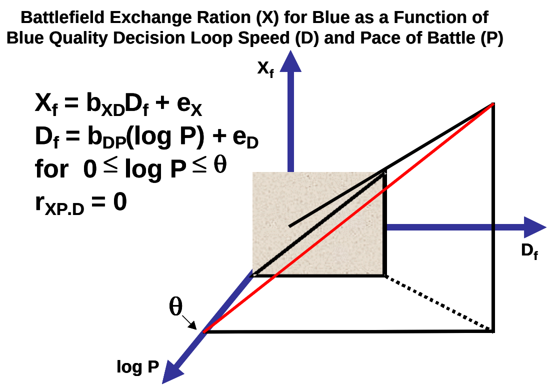


Figure 4.   Battlefield Exchange Ratio (X) by Loaded (P) Decision Loop (D).

Thus, ignoring considerations of weapons and sensor positions and ranges, the pace of battle workload threshold of the superordinate CAS depends on the sum of the workload thresholds of its component subordinate CAS members.

$$\theta_s = k(\theta_1 + \cdots + \theta_i + \cdots + \theta_n) \qquad (13)$$

Now considering the superordinate CAS composed of several subordinate CAS members, D_1,.D_i,..D_n, we may also ask what is the loaded quality decision loop speed of the larger system. At the heart of the matter are the shared situation awareness, N_s, and shared plans, N_p, between the subordinate CAS members. To contribute to the super CAS the n sub CAS members must each share situation view and plan view, and by implication network connection, with some other member of the super CAS. Consider the matrix composed of degrees of shared awareness of the battlespace between all pairs of CAS units, $\mathbf{N_s}$. Post multiplying this matrix by the matrix composed of shared plan views, $\mathbf{N_p}$, yields a matrix showing the degree of shared quality decision components across all units. When this shared product matrix is premultiplied by the vector composed of quality decision loop speeds, **d**, for each of the individual CAS units, the resulting vector indicates the shared quality decision processing contribution of each subunit to the superordinate CAS as a whole. Finally, when this vector is premultiplied by the vector above, $\boldsymbol{\theta}$, composed of workload thresholds for each subordinate CAS, the resulting scalar represents the loaded quality decision loop speed of the superordinate CAS, D_s:

$$D_s = \boldsymbol{\theta} \left(\mathbf{d} \left(\mathbf{N_s} \, \mathbf{N_p} \right) \right) \qquad (14)$$

5 CONCLUSIONS

We have assembled empirical evidence from controlled experiments, military exercises and stochastic simulation runs demonstrating that, in addition to weaponry, changes in command, control and communications significantly impact combat outcome. We have found it revealing to conceive of military forces as consisting of Complex Adaptive Systems with more or less automated schema for situation assessment and action planning which can be shared across a communications network along with sensor reports and weapons use for effective combat action. We have advanced several major hypotheses with supporting evidence on how C2 variables impact combat outcome: C2 as a force multiplier; the impact of quality decision loop speed; the components of information superiority over an adversary; decision limitations of information overload; speed limitations of communications channel capacity; and the role of a shared COP and shared plan view in enabling super ordinate CAS construction for Net Centric Warfare. Each of these hypotheses merits further examination and testing; but there can be no doubt that wargame simulators, like JWARS, must account for the observed regularities in the impacts of C2 on combat outcome to provide validity for their output.

REFERENCES

[Alberts, et al., 2001] D. Alberts,, J. Garstka, R. Hayes, and D. Signori, *Understanding Information Age Warfare*: DoD Command and Control Research Program, Washington, D.C., August 2001.

[Bond, 1998] BG W. Bond, *Army Digitization Overview*, Briefing to USD(A&T), Pentagon, Washington, D.C., May 20, 1998.

[Boyd, 1987] John R. Boyd, *An Organic Design for Command and Control*, Unpublished Lecture Notes, 1987

[Campbell & Stanley, 1963] D. Campbell and J. Stanley, *Experimental and Quasi-Experimental Designs for Research,* Chicago, IL: Rand McNally, 1963.

[Cebrowski & Garstka, 1998] VADM. A. Cebrowski, and J. Garstka, *Network Centric Warfare: Its Origins and Future,* Proceedings of the Naval Institute 124:1, pp 28-35, 1998.

[Garstka, 2000] J. Garstka, *Net Centric Warfare: An Overview of Emerging Theory*, Phalanx, Vol. 33, No.4, December 2000.

[Gell-Mann, 1994] M. Gell-Mann, *Complex Adaptive Systems* in G. Cowan, D. Pines, D. Meltzer, Complexity: Metaphors, Models, and Reality, Cambridge, MA: Perseus Books, pp. 17-46, 1994.

[Hayes, Strack, et al. 1982] R. Hayes, C. Strack, et al., with Defense Systems, Inc., *Theater Headquarters Effectiveness: Its Measurement and Relation to Size, Structure, Function, and Linkages*, McLean, VA, 1982.

[Hiniker, 1991] Paul Hiniker, *HEAT Experiments: Use of the Experimental Method to Evaluate the Effectiveness of HQ C2 Insertions*, Proceedings of the JDL BRG C2 Research Symposium, pp 323-331, July 1991.

[Hiniker, 1994] Paul Hiniker, *A Cross-Experimental Investigation of Technology for Effective Command Decision-Making,* Proceedings of the First Workshop in Command Information Systems. Defense Research Agency, Oxford, England, 1994.

[Hiniker, 1998] Paul Hiniker, *The Common Operational Picture As Evolving Schema for Command Centers As Complex Adaptive Systems*, Proceedings of the 4th International Command and Control Research and Technology Symposium, Stockholm, Sweden, September 1998.

[Hiniker, 2001] Paul Hiniker, *The Loaded Loop: A Complex Adaptive Systems Model of C2 Processes in Combat*, Paper presented at RAND Modeling of C2 Decision Processes Workshop, McLean, VA, July 2001.

[Hiniker & Entin, 1990] Paul Hiniker and E. Entin, *The Effects of Shared Battle Graphics on Team Performance in Crisis Situations: HEAT Experimental Results*, Proceedings of the JDL BRG C2 Symposium, July 1990.

[Hiniker & Entin, 1992] Paul Hiniker and E. Entin, *Examining Cognitive Processing in Command Crises: New HEAT Experiments on Shared Battle Graphics and Time Tagging*, Proceedings of the JDL BRG C2 Research Symposium, July 1992.

[HQ USAF, 1997] HQ USAF, *JTIDS Operational Special Project Report to Congress*, Washington, D.C. December 1997.

[HQ USMC, 1996] HQ USMC, C2 Concept Paper, *Command and Control*, 1996.

[LaPorte & Noyes, 2000] LtGen L. LaPorte and Col W. Noyes, *Operation Centric Warfare: The Bold Shift*, Army, Vol. 50 No 8, pp 16-20, 2000.

[Lawson, 1978] J. S. Lawson, *A Unified Theory of Command and Control*, 41st Military Operations Research Symposium, 11-13, July 1978.

[Levis, et al.,, 1987] A. Levis, A. Louvet, and J. Casey, *Experimental Investigation of the Bounded Rationality Constraint*, Proceedings of the JDL BRG C2 Research Symposium, pp 235-241, July 1987.

[Lewin, 1999] R. Lewin, *Complexity,* Chicago: Univ. of Chicago Press, 1999.

[Martin, undated] B. Martin, *The Schema,* in Cowan, G. et al. Complexity.

[Maxwell, 2000] D. Maxwell, *An Overview of the Joint Warfare System (JWARS*), Phalanx, Vol. 33 No.3, pp. 12-14, September 2000.

[OPNAV/N6, 2001] OPNAV/N6, *Advanced C2 Study: Game IV Report*, 2001.

[Perla, 2000] P. Perla, et al., *Gaming and Shared Situation Awareness*, Center for Naval Analysis Report, November 2000.

[Perry, et al., 2001] W. Perry, R. Darilek, J. Bracken, J. Gordon and B. Nichiporuk, *Measures of Effectiveness for the Information-Age Army,* Santa Monica, CA: RAND, 2001.

[Serfaty, et al., 1988] D. Serfaty, E. Entin and R. Tenney, *Planning with Uncertain and Conflicting Information*, (HEAT), Proceedings of the JDL BRG C2 Symposium, Monterey, CA, July 1988.

[Van Trees, 1988] H. Van Trees, C3 *Systems Research: A Decade of Progress*, Proceedings of the JDL BRG C2 Research Symposium, pp 17-38, July 1988.

[Waldrop, 1992] M. Waldrop, *Complexity,* New York, Simon and Schuster, 1992.

[Wohl, 1981] J. G. Wohl, *Force Management Decision Requirements for Airforce Tactical Command and Control*, IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-11, No. 9, pp 618-639, September 1981.