

16th ICCRTS: “Collective C2 in Multinational Civil-Military Operations”

Defining and Measuring Cognitive-Entropy and Cognitive Self-Synchronization

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Abstract

Modern military operations require to operate in a coalition environment in which Network-Centric principles intrinsically apply. These operations were coined as *Complex Endeavors* (Alberts and Hayes, 2009) – characterized by multiple chains of command, lack of understanding of all cause-effect relationships and unpredictability - and new ways of conducting C2 have been proposed (SAS-065, 2010) aiming to achieve high levels of *shared awareness and enabling self-synchronization across the range of participating entities* (Alberts and Hayes 2009, pp.106).

We consider the aspect of *self-synchronization* (Alberts and Hayes, 2006) a key one in the context of modern operations and in performing C2 assessments. Based on (Manso and B. Manso 2010), we present an approach to define it and measure it objectively in the cognitive domain, namely as *Cognitive-Entropy* (CE) – that measures the degree of collective disorder in self-synchronization in the cognitive domain – and *Cognitive Self-Synchronization* (CSSync), its counterpart – that measures the degree of collective order in the cognitive domain. Moreover, we further identify aspects that may enable and inhibit CSSync, together with a preliminary assessment on the associated impact on cost. The results presented are based on consistent outcomes observed from experiments conducted in the context of the NATO NEC C2 Maturity Model (SAS-065 2010).

Topics:

Experimentation, Metrics, and Analysis
Collaboration, Shared Awareness, and Decision Making
Concepts, Theory, and Policy

1 INTRODUCTION

Modern military operations cover a broad spectrum of missions that are beyond conventional warfare and also include peace-keeping and large-scale disaster response operations. Considering also that the world becomes more and more connected and interdependent (a result of globalization), characteristics of military operations resemble those of *Complex Endeavors* (Alberts and Hayes, 2007), that is, they include (1) military and non-military participants with multiple independent “chains of command” and different objective functions, and (2) lack of understanding of cause-effect relationships and unpredictability of effects. In such an environment, Network-Centric principles and their implications intrinsically apply. These are depicted in the Network Centric Warfare (NCW) value-chain in Figure 1 (SAS-065, 2010, pp. 27).

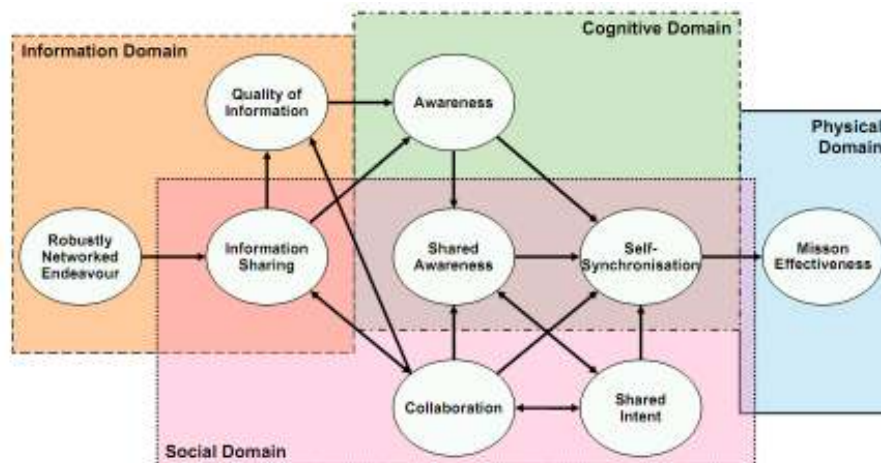


Figure 1 - NCW Value-Chain

A key aspect of the NCW value-chain consists of a force's ability to Self-Synchronize, that is, *the ability of a well-informed force to organize and synchronize complex warfare activities from the bottom up* (Cebrowski, Arthur K. and Garstka, 1998). This definition comprises two relevant aspects:

- Synchronization, as an output characteristic of the C2 processes that arrange and continually adapt the relationships of actions (including moving and tasking forces) in time and space in order to achieve the established objective(s). [...] Synchronization takes place in the physical domain (Alberts et. al., 2001).
- Self, as being a result from the bottom up (in this context, as a result of developing shared awareness enabled by networking) *without the need for guidance from outside the system* (Atkinson and Moffat, 2005).

Synchronization has been a *fundamental concept in warfare throughout history* but achieving it is *becoming more challenging* due to the *increased complexity, growing heterogeneity, and a faster pace of events* (Alberts et. al., 2001).

Thus, we consider the aspect of *Self-Synchronization* a key one in the context of modern operations and in performing C2 assessments. We also consider that its application is beyond the physical domain and covers the cognitive domain as well. Therefore, we aim, in this paper, to propose a way to measure it in the cognitive domain and, furthermore, to identify a set of enablers and inhibitors to its development.

In this paper, we start by introducing the concepts of Cognitive Entropy and Cognitive Self-Synchronization and a method to measure them based on the Kolmogorov Complexity. Then we further identify the aspects that may influence them, either as enablers or inhibitors, and their associated costs. For that, we will resort to past experimentation data to test the assumptions made. We finalize by presenting the main conclusions and suggestions for future work. Additional information about Kolmogorov Complexity is provided in Annex A. Next, we introduce ELICIT, the experimentation platform used to measure and observe Cognitive Entropy and Cognitive Self-Synchronization.

1.1 Introducing ELICIT

ELICIT is a research and experimentation programme developed for the CCRP to conduct research related with collaboration, information sharing and trust, and to test hypothesis related with edge and hierarchical (traditional) command and control practices (Ruddy 2007).

The ELICIT web-version platform (webELICIT) (Ruddy 2008) currently includes human and/or software-agent subjects (17 in the original version) that may be rearranged in terms of their organization structure (e.g., hierarchy and EDGE) whose task is discovering the “who”, “what”, “when”, and “where” of an attack. For that purpose, pieces of information (i.e., *factoids*) necessary to determine the solution are provided to subjects. The subjects may then opt to share factoids with others so that more information becomes available. Only by sharing information subjects can obtain required levels of information quality to solve the problem.

webELICIT was used as a network-centric experimentation platform since it provides easy manipulation and setup of organization models, control of communications, and, more importantly, a clear mapping with the theory of NCW, including a subset of the C2 CRM where several variables of interest are observable, including: Quality of Individual and Shared Information Position, Information Distribution, Patterns of Interaction, Quality of Individual and Shared Understanding, Quality of Interactions, Self-Synchronization, Mission Effectiveness and Mission Efficiency (given Effectiveness) (Manso and Nunes 2007) (McEver, Hayes and Martin 2007) (Martin and McEver 2008).

2 MEASURING SELF-SYNCHRONIZATION IN THE COGNITIVE DOMAIN

Self-Synchronization in the Cognitive Domain was introduced in the work conducted for the validation of N2C2M2 (Manso and B. Manso 2010) and was based on Moffat’s work towards developing a *knowledge metric* (Moffat 2003) to measure the amount of uncertainty in a probability distribution (based on Shannon’s Information Entropy). The corresponding variable was named as *Cognitive Self-Synchronization* (CSSync) (its counterpart being *Cognitive Entropy* (CE)). CSSync was applied in the context of ELICIT experiments.

First, we will present a more exact definition for CSSync based on the scientific field of Complexity theory, namely, the Kolmogorov complexity (see Annex A) since the latter *is a measure of the descriptive complexity of an object* (Cover and Thomas 1991).

Our goal is to measure the descriptive complexity of the awareness of a group of individuals – that is, the result of their cognitive process – over time. The formulation will be presented having as basis the application of CSSync and CE to the ELICIT experiments.

Kolmogorov Complexity, Shannon Entropy and CE are closely related so we start by defining CE.

Defining Cognitive Entropy

We apply the Kolmogorov Complexity formulation to ELICIT as the game unfolds over time t , in the cognitive domain.

We assume that the ELICIT game is played by 17 subjects (that is, $N=17$)¹.

We define four ‘solution spaces’ corresponding to the four parts of the overall solution (*who, what, where and when*). *When*, in particular, is further decomposed into *when-hour, when-day* and *when-month*.

¹ Although this is the typical configuration for ELICIT, the number of subjects may change. N may then be replaced by the number of subjects.

For a given solution space, each player at time t will have a description of the solution at time t (including the null case where no solution is given) – we call this an ID in ELICIT. For each solution space, there are K possible choices, and a particular choice is represented by k ($1 \leq k \leq K$)

For each solution space i ($1 \leq i \leq 4$) at time t , we thus define:

$S(i, t, k)$ = Number of IDs for solution space i at time t of type k

For example, if we consider the ‘who’ solution space, and there are M identical IDs for a ‘who’ of type k , then $S(i, t, k) = M$

The probability of this description is defined as:

$$p(i, t, k) = \frac{S(i, t, k)}{17}.$$

Note that $-\log p(i, t, k)$ (the expected description length) in this case will be small and positive where there are several coincident IDs, falling to zero if all 17 players give the same ID.

The total number of positive IDs is given by $\sum_{k=1, S(i, t, k) \neq 0}^{k=K} S(i, t, k)$.

The number of players who do not make a positive ID for solution space i is then given by $17 - \sum_{k=1, S(i, t, k) \neq 0}^{k=K} S(i, t, k)$. This parcel will be named as ‘uncertainty parcel’ and provides an indication of the level of uncertainty of a group towards any possible ID, assuming that uncertainty is related to unwillingness to make a positive ID.

For the null case (no ID given) we define the probability of this description as:

$$p(i, t, k = \emptyset) = \frac{1}{17} \text{ where } \emptyset \text{ denotes the null set.}$$

In this case the expected description length of each null ID is $-\log\left(\frac{1}{17}\right) = \log 17$ and is as thus large and positive as it can be. Thus if many players do not supply an ID (an event which requires a long description length to lay out), then we assume the cognitive entropy has increased significantly.

For example, at the beginning of the game, when there are no positive IDs, there are 17 such null IDs, each with a description length of $\log(17)$.

We now define the cognitive entropy CE for solution space i at time t as

$$CE(i, t) = - \left\{ \sum_{k=1, S(i, t, k) \neq 0}^{k=K} p(i, t, k) \log p(i, t, k) + \left\{ 17 - \sum_{k=1, S(i, t, k) \neq 0}^{k=K} S(i, t, k) \right\} \frac{1}{17} \log \frac{1}{17} \right\}$$

This expression then represents the expected description length (or cognitive entropy) for our solution space corresponding to each of the possible values of $p(i, t, k)$, including all of the null IDs (each taken separately in the summation).

Defining Cognitive Self-Synchronization

Cognitive Self-Synchronization (CSSync) will measure the amount of order of a group at a particular time t towards determining the problem (i.e., finding the *who*, *what*, *where* and *when* of an attack). Note that our emphasis here is on the synchronization of the positive IDs made by the subjects. Treating these subject identifications as a measure of uncertainty, the function we will use to represent CSSync, based on the Cognitive Entropy and Kolmogorov Complexity presented in the previous section, is the following:

$$CSSync_{ProblemSpace}(i,t) = 1 - \frac{CE(i,t)}{Max_Disorder_{ProblemSpace}}$$

CSSync is measured for each identification input field i (i.e. each *ProblemSpace* i). Note that $Max_Disorder_{ProblemSpace}$ refers to the maximum entropy value (described before) and is used to normalize CSSync to a value between 0 and +1 (the addition of 1 to the relationship is made so that $CSSync \in [0,1]$).

The values at the boundaries may be interpreted as follows:

- CSSync=0 means the system is fully disordered.
- CSSync=1 means the system is fully synchronized.

We assume that any group operating in ELICIT has an initial state of maximum disorder (maximum entropy), that is:

$$Max_Disorder_{ProblemSpace} = -\sum_{i=1}^N \frac{1}{N} * \log\left(\frac{1}{N}\right) = \log(N).$$

In our case (N=17), $Max_Disorder_{ProblemSpace} = \log 17$

$$\text{Thus } CSSync_{ProblemSpace}(i,t) = 1 - \frac{CE(i,t)}{\log 17}$$

The measure for the overall CSSync(t) at time t is simplified to be the sum of the partial $CSSync_{ProblemSpace}$ values, that is:

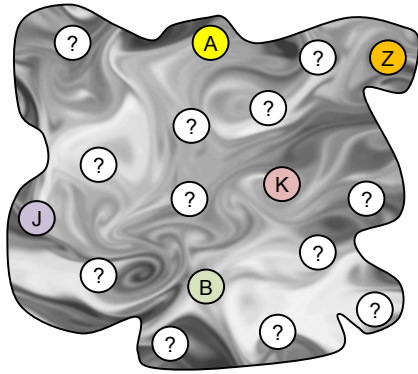
$$CSSync(t) = 0.25 * \sum_{i=ProblemSpace} CSSync(i,t) \quad (\text{weights are used to normalize total CSSync})^2$$

As the game progresses, individuals share information and collaborate and, as a result, subjects develop awareness and make identification attempts, some of which equivalent. In such a scenario, the cognitive disorder decreases (or, the cognitive synchronization increases) and the group is said to be converging to a common understanding of the problem. Ultimately, if all subjects provide the same identification for all of the problem spaces, we may conclude that the system was able to converge and fully self-synchronize at some time t (assuming no external influence is exerted, as is the case in ELICIT). In such a scenario we have a description length of zero for all problem spaces, with $CE(i,t) = 0$ for all i .

Thus all subjects have the same understanding of the problem and $CSSync(t) = 1$.

² We are assuming that the four solution spaces are independent so that we can add the entropies from each of the four solution spaces to give an overall entropy for the state of the game at time t . Formally this is not strictly true since the solution spaces are linked, but the sum of the entropies is always an upper bound and the sum usually works well in practice as a measure of merit.

The next figures exemplify measurement of CSSync for simple static situations ranging from total disorder to complete order. In these cases there is only one problem space. Thus we take $i = 1$ and time $t = 0$. Note also that in all calculations, logs are taken to base e (i.e., we use natural logarithms, denoted \ln).

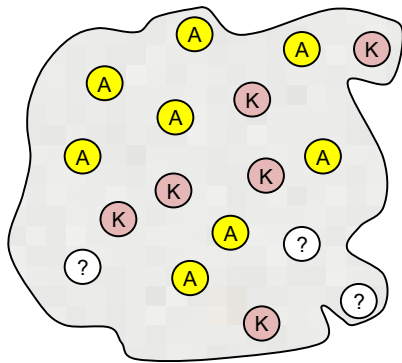


k \	A	B	J	K	Z	Unknown
S (1,0,k)	1	1	1	1	1	17 - 5 = 12
p (1,0,k)	1/17	1/17	1/17	1/17	1/17	12 times 1/17

$$CE(1,0) = -\left\{5 * \left(\frac{1}{17}\right) * \log\left(\frac{1}{17}\right) + (17 - 5) * \left(\frac{1}{17}\right) * \log\left(\frac{1}{17}\right)\right\} = \log(17)$$

$$CSSync(0) = 1 - \left(\frac{\log 17}{\log 17}\right) = 0$$

Fully-disordered system³

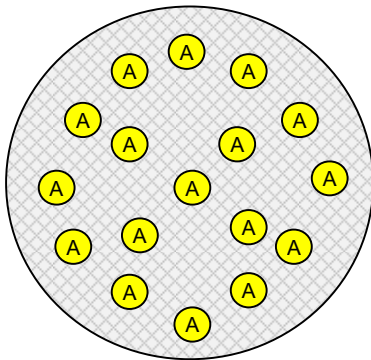


k \	A	K	Unknown
S (1,0,k)	8	6	17 - 14 = 3
p (1,0,k)	8/17	6/17	3 times 1/17

$$CE(1,0) = -\left\{\frac{8}{17} * \log\left(\frac{8}{17}\right) + \frac{6}{17} * \log\left(\frac{6}{17}\right) + (17 - 14) * \left(\frac{1}{17}\right) * \log\left(\frac{1}{17}\right)\right\} = 0.53$$

$$CSSync(0) = 1 - \left(\frac{0.53}{\log 17}\right) = 0.57$$

Partially ordered system



k \	A	Unknown
S (1,0,k)	17	0
p (1,0,k)	17/17	0

$$CE(1,0) = -\left\{\left(\frac{17}{17}\right) * \log\left(\frac{17}{17}\right)\right\} = 0$$

$$CSSync(1,0) = 1 - \left(\frac{0}{\log 17}\right) = 1$$

Fully-synchronized (ordered system)

Figure 2 – CE and CSSync Calculation Examples

³ Picture shows the concentration of a passive scalar in isotropic turbulence (Brethouwer 2000).
Source: http://www.efluids.com/efluids/gallery/gallery_pages/iso_turbulence_page.htm

3 ENABLERS AND INHIBITORS OF SELF-SYNCHRONIZATION: RESULTS FROM EXPERIMENTS

In the previous sections, we defined the CE and CSSync variables and presented ways to quantitatively measure them. Considering the relevance of the emergence of Self-Synchronization (in the Cognitive Domain) it becomes pertinent to raise the following questions:

- Q1: What aspects enable the emergence of Self-Synchronization?
- Q2: What aspects inhibit the emergence of Self-Synchronization?
- Q3: What is the associated cost to Self-Synchronize?

For that, we revisit again the NCW tenets stating that a robustly networking an enterprise enable self-synchronization (Alberts and Hayes 2007), therefore linking these two aspects. The NATO SAS-065 group further explored this link by defining several C2 Approaches⁴ (SAS-065 2010) and their expected implications in C2. Subsequently, experimentation work was conducted using the ELICIT platform to validate some of the model early hypothesis (Manso and B. Manso 2010) with relevant findings for CE and CSSync.

In this section, we start by introducing the experimentation work performed in the context of the N2C2M2, then we will present a model depicting the influencing factors for CE and CSSync and, finally, we will present answers for the above questions based on the experimentation results within the scope of ELICIT.

3.1 N2C2M2 Experiments and a Model for CSSync

For the purpose of validating the N2C2M2 developed by the NATO group SAS-065, a set of activities were conducted including experimentation using the ELICIT platform. The work in ELICIT consisted in instantiating the five C2 Approaches and observing if the observed outcomes were consistent with the model. Namely, the model stated that increasing the C2 Approach consists in (i) increasing the distribution of information, (ii) broadening the patterns of interaction and (iii) distributing the allocation of decision rights across the collective. In terms of the NCW value chain, increasing the C2 Approach corresponds to improving the way an organization is robustly networked with subsequent implications for several variables of the value chain, including self-synchronization.

The detailed work and results of the N2C2M2 experiments using the ELICIT platform were presented in (Manso and B. Manso 2010). The focus of this section will be on the self-synchronization aspects in the cognitive domain. For that, a model is depicted in Figure 3 linking the questions posed in the beginning of this section to the N2C2M2 experiments and allowing inferences to be made. The presented model is an adaptation of the model used in the ELICIT N2C2M2 experiments.

For a problem solving game such as ELICIT, the positioning of the system into a given C2 Approach mainly consisted in setting initial conditions in terms of network access (allowed interactions), the organization model (which affects the distribution of information) and the allocation of decision rights. However, note that this process depended on the subjects' willingness⁵ to comply with the instructions and achieve the intended C2 Approach throughout the experiment.

⁴⁴ More specifically, five: CONFLICTED C2, DE-CONFLICTED C2, COORDINATED C2, COLLABORATIVE C2 and EDGE C2.

⁵ Human subjects were used in the ELICIT N2C2M2 experiments.

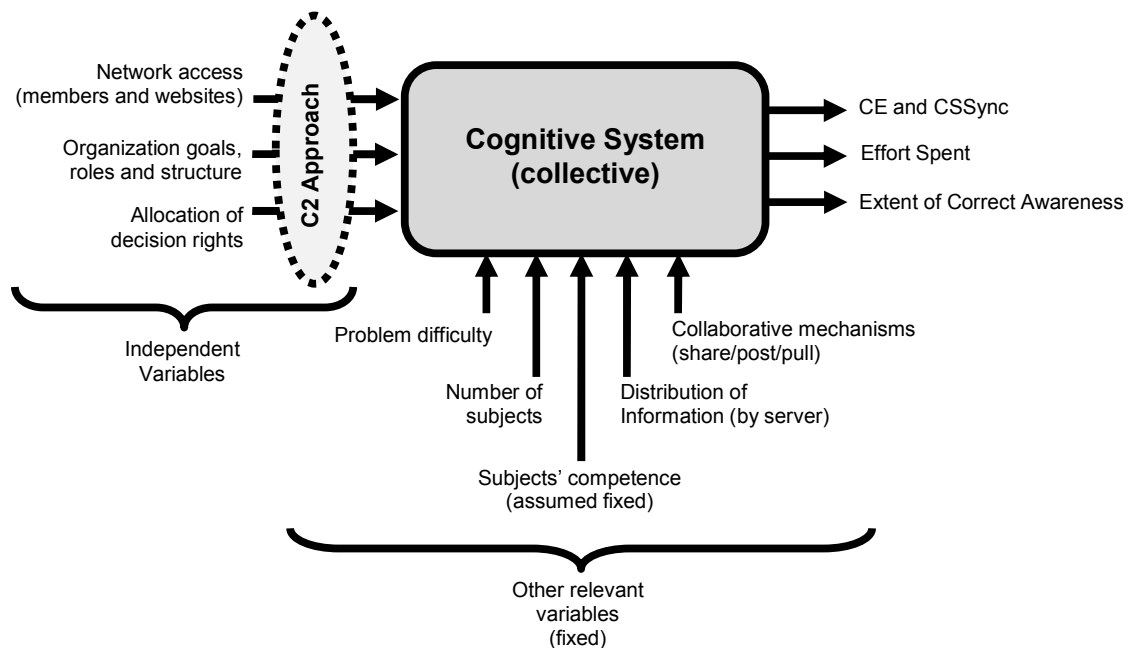


Figure 3 – Experimentation Model for CE and CSSync

Moreover, we identified additional variables that we consider relevant in the scope of CE and CSSync:

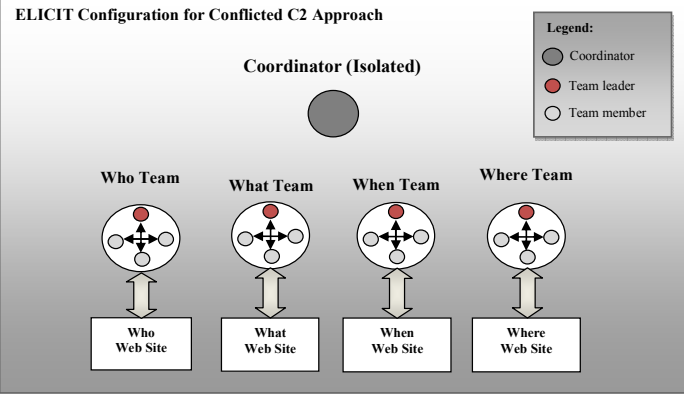
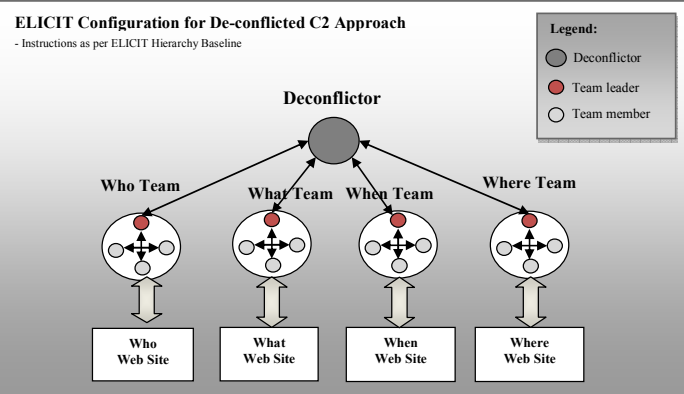
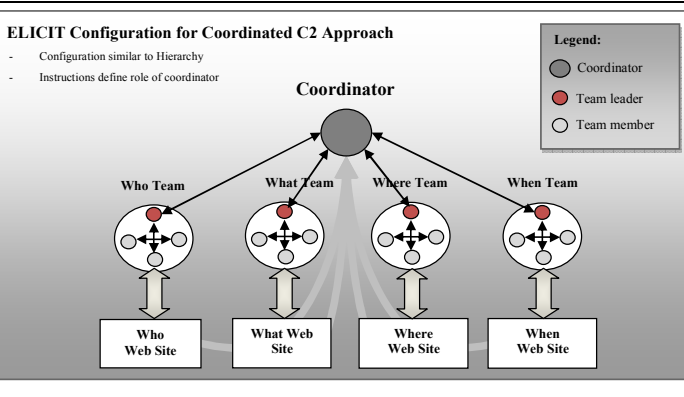
- **Problem Difficulty:** a more difficult problem should generate more CE than an easier one. The difficulty of the ELICIT problem set was analyzed in (Alston 2010) and was characterized as tame (an unambiguous solution may be found) and simple (all information is available and is unambiguous). Nevertheless, the way the information is distributed, the dynamics generated by subjects and amount of information actually accessible (usually below 80%) results in a difficult problem to solve from the subjects' perspective.
- **Number of Subjects (N):** the smaller the number of subjects (N) the less the maximum value of CE (i.e., $\log N$).
- **Subjects' competence:** the lower the subjects' competence, the higher the CE. Competence may result from a subject's training, experience and familiarity towards given problem. For the ELICIT experiments, no special abilities were required to solve the problem and prior experience was not considered relevant.
- **Distribution of Information (by server):** the way information is distributed by the ELICIT server impacts access to information, a necessary asset to build shared awareness (and CSSync).
- **Collaborative mechanisms (share/post/pull):** rich collaborative mechanisms aid subjects' interactions and help build shared awareness (and CSSync).

The above listed variables were kept fixed across the experiments, except Subjects' competences (which were assumed as fixed). Clearly, future work should further exploit manipulation of those variables - as well as extending the observation of variables to other intermediate ones - and measure their influence in terms of CE and CSSync.

For this work, we will focus on the available experimentation data which resulted from positioning a system at specific C2 Approaches and measure its effects in terms of CE and CSSync. Moreover, we will present results for "Effort Spent" and "Extent of Correct Awareness", the latter being what we consider as the most important measure of effectiveness in ELICIT.

3.2 Experiments Design (from N2C2M2 Validation)

The experiments design for the N2C2M2 validation in ELICIT instantiated the model's five C2 approaches and assessed their performance by testing each of the C2 approaches' ability to solve a problem (i.e., determine the *who*, *what*, *where* and *when* of a terrorist attack). The assessment was based on measurement of variables defined in the N2C2M2 and the C2 CRM (SAS-050 2006). The manipulation made to instantiate the five C2 approaches is presented in Table 1. The experiments design is detailed in (Manso and B. Manso 2010).

Entities Configuration	Variables Manipulation (*):
<p>ELICIT Configuration for Conflicted C2 Approach</p>  <p>Legend: ● Coordinator ● Team leader ○ Team member</p>	<ul style="list-style-type: none"> • NP: Teams exclusive access to their website. Non-interoperable (no cross-teams communications). • ISC: None outside teams. • ADR: None (independent decision rights within teams only) • <u>Success Criterion</u>: Each Team pursues independent goals. Success occurs if each Team leader finds the correct solution to his problem space.
<p>ELICIT Configuration for De-conflicted C2 Approach</p> <p>- Instructions as per ELICIT Hierarchy Baseline</p>  <p>Legend: ● Deconflictor ● Team leader ○ Team member</p>	<ul style="list-style-type: none"> • NP: Minimum connectivity. Stove-pipe: between Team leaders and Information Broker. Teams exclusive access to their websites. • ISC: Isolated goals, but factoids interdependency <u>should</u> enable weak/minimum interactions, between stove-pipes (Deconflictor and Team leaders). • ADR: Established constraints (share what is relevant to other teams). Decision allocated to each Team leader. Team specialized problem space. • <u>Success Criterion</u>: Each Team pursues independent goals. Success occurs if each Team leader finds the correct solution to his problem space
<p>ELICIT Configuration for Coordinated C2 Approach</p> <p>- Configuration similar to Hierarchy - Instructions define role of coordinator</p>  <p>Legend: ● Coordinator ● Team leader ○ Team member</p>	<ul style="list-style-type: none"> • NP: Minimum connectivity. Stove-pipe: between Team leaders and coordinator. Teams exclusive access to their websites. Coordinator access to all websites. • ISC: Collective goals centralized by function (Coordinator, assisted by Team leaders) <u>should</u> enable stronger interactions among hierarchies and subordinates (Coordinator and Team leaders and Team members). • ADR: Centralized (in Coordinator). Team specialized problem space. • <u>Success Criterion</u>: Organization success depends on the Coordinator finding the correct solution.

<p>ELICIT Configuration for Collaborative C2 Approach</p> <ul style="list-style-type: none"> - Players have access to all websites - Feature added that allows players to evaluate factoids and share /post evaluations - Instructions define role of coordinator 	<ul style="list-style-type: none"> • NP: Fully connected and interoperable. Existing P2P connectivity between all individuals. Shared team websites. • ISC: Collective goals set to Coordinator and Team leaders together with unrestricted communications policy (across individuals with shared websites and factoids evaluation) <u>should</u> increase and enrich interactions and collaboration among individuals (still with stronger ties expected between Coordinator and Team leaders). • ADR: Distributed and collaborative. Across Team leaders and coordinator/facilitator (CF). CF works in all problems. • <u>Success Criterion</u>: Organization success depends on the Coordinator finding the correct solution to all problem spaces OR Team leaders finding the correct solution to their problem space.
<p>ELICIT Configuration for Edge C2 Approach</p>	<ul style="list-style-type: none"> • NP: Fully connected and interoperable. Existing P2P connectivity between all individuals. Shared team websites. • ISC: Collective goals set to all individuals (no predefined roles) and unrestricted communications policies (across individuals with shared websites and factoids evaluation) <u>should</u> increase and enrich interactions and collaboration among all individuals. • ADR: Fully distributed / not explicit (per individual) and dynamic. Individuals choose which part (or parts) of the problem space they work. • <u>Success Criterion</u>: Organization success depends on the individuals' IDs plurality being correct in each problem space.

(*) NP: Network Performance, ISC: Information Sharing and Collaboration, ADR: Allocation of Decision Rights (to the Collective), SC: Success Criterion

Table 1 – ELICIT Experiment Design: a brief overview

3.3 Measurements: CE and CSSync

The measurements for CE and CSSync are presented in Table 2. The first column provides a unique identifier of each run and also includes the C2 Approach that corresponds to a given N2C2M2 maturity level (e.g., L1-03 refers to the 3rd run of level 1 C2 Approach – Conflicted C2).

Cognitive Self-Synchronization								
ID	WHO	WHAT	WHERE	WHEN (t)	WHEN (d)	WHEN (m)	OVERALL	Uncertainty Parcel ⁶
L1-01	0.10	0.09	0.14	0.10	0.00	0.00	0.088	0.56
L1-02	0.10	0.07	0.06	0.17	0.00	0.03	0.071	0.69
L1-03	0.00	0.00	0.00	0.00	0.03	0.03	0.004	0.73
L2-01	0.07	0.03	0.03	0.07	0.00	0.03	0.039	0.70
L2-02	0.00	0.00	0.13	0.17	0.07	0.03	0.052	0.67
L2-03	0.31	0.12	0.28	0.03	0.35	0.22	0.219	0.48
L2-04	0.23	0.17	0.21	0.20	0.07	0.12	0.179	0.52
L3-01	0.06	0.14	0.14	0.07	0.00	0.10	0.097	0.62
L3-02	0.17	0.14	0.23	0.00	0.07	0.07	0.145	0.49
L3-03	0.06	0.10	0.23	0.22	0.12	0.07	0.127	0.61
L3-04	0.25	0.17	0.34	0.20	0.00	0.12	0.215	0.38
L4-01	0.33	0.38	0.42	0.77	0.48	0.55	0.416	0.22
L4-02	0.53	0.38	0.25	0.62	0.20	0.48	0.386	0.30
L4-03	0.18	0.14	0.48	0.12	0.06	0.03	0.217	0.47
L4-04	0.28	0.29	0.39	0.48	0.34	0.41	0.331	0.36
L5-01	0.41	0.33	0.58	0.69	0.55	0.00	0.424	0.17
L5-02	0.35	0.43	0.40	0.84	0.55	0.03	0.401	0.15
L5-03	0.40	0.41	0.32	0.77	0.22	0.55	0.398	0.24

Table 2 – CE and CSSync measurements

The CSSync average value per C2 Approach, including its maximum and minimum values, are presented in Figure 4 and Table 3 below.

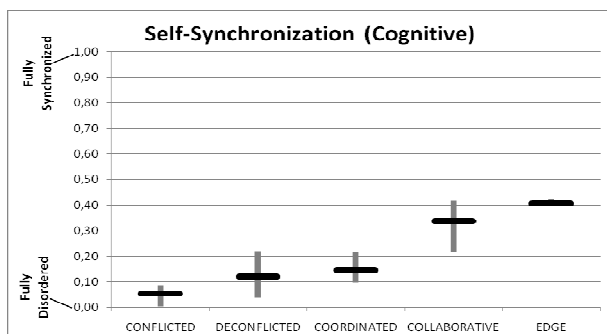


Figure 4 - Cognitive Self-Synchronization

APPROACH	Mean	MIN	MAX
CONFLICTED	0.05	0.00	0.09
DECONFLICTED	0.12	0.04	0.22
COORDINATED	0.15	0.10	0.22
COLLABORATIVE	0.34	0.22	0.42
EDGE	0.41	0.40	0.42

Table 3 - Average value of CSSync per C2 Approach

⁶ Uncertainty parcel (normalized) related to individuals that didn't provide ID attempts.

The data collected does not allow a full statistical analysis, however some preliminary conclusions can be drawn as follows:

- On average, the CSSync increases when the C2 Approach increases: EDGE C2 and CONFLICTED C2 have respectively the highest and the lowest value for CSSync.
- EDGE C2 has the lowest variability between MIN and MAX (i.e., 0.02), therefore obtaining the most consistent results from all C2 Approaches.
- The uncertainty parcel (i.e., entropy parcel related to individuals that didn't identify) decreases as the C2 approach increases: its ranges between 0.73 (in L1-03) and 0.15 (in L5-02). This indicates that organizations operating at lower levels of maturity fail in generating any awareness across members (or their members are less willing to make awareness attempts).

In Figure 5 (page 13), we present the evolution of CSSync and its 'uncertainty parcel' over time for a run from each of the five C2 Approaches. These presentations allow additional considerations, even if only applicable for these particular runs:

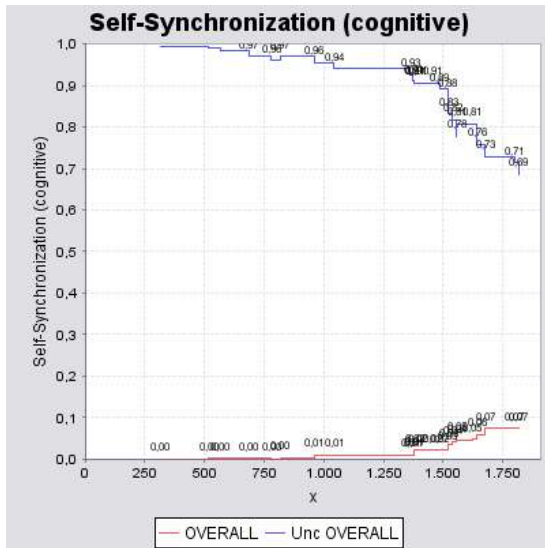
- CSSync in EDGE L5-02 developed earlier and at a higher rate than any other C2 Approach.
- CSSync in COLLABORATIVE L4-04 had a late increase but achieved a higher than average end-value (0.331).
- CSSync in DECONFLICTED L2-03 increased earlier than in COORDINATED L3-04.
- CSSync in CONFLICTED L1-02 barely developed (ended in 0.071).
- CSSync increases over time (a direct result of increased access to information across subjects).

Based on the data collected, we will now provide explanations for the questions raised earlier, in the scope of the ELICIT experiments.

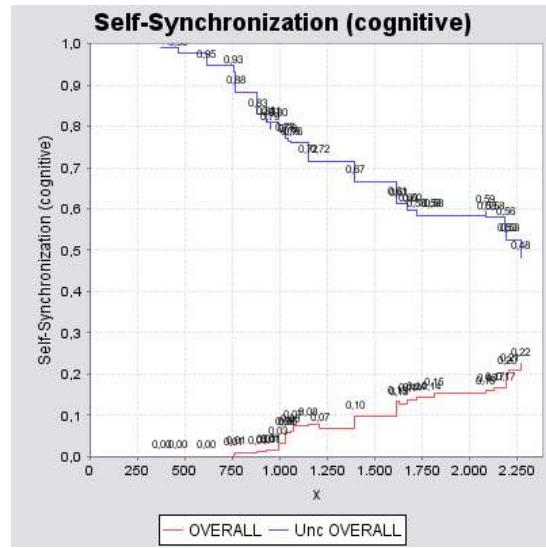
- *Q1: What aspects enable the emergence of Self-Synchronization?*
- *Q2: What aspects inhibit the emergence of Self-Synchronization?*

It seems that a direct relation exists between the C2 Approach adopted and the resultant Self-Synchronization achieved in the cognitive domain (CSSync).

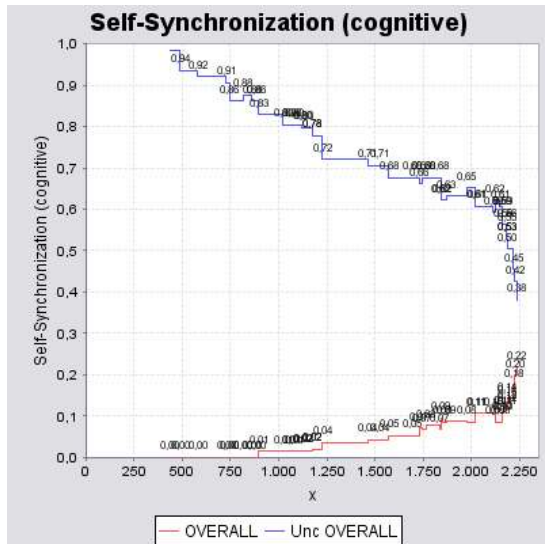
From the data we have available, we may interpret this as a result of moving up in terms of the C2 Approach; a collective removes constraints that inhibit information sharing, interaction, allocation of decision rights and the development of shared awareness and, at the same time, sets enablers that influence an increase in their members' pro-activeness. This in turns contributes to more information sharing, better levels of shared awareness and increased CSSync. This is confirmed when increasing the C2 Approach from CONFLICTED C2 through DE-CONFLICTED C2, COORDINATED C2, COLLABORATIVE C2 and EDGE C2. The latter case is of particular interest and its analysis worthy to be further elaborated. In the ELICIT N2C2M2 experiments, COLLABORATIVE C2 and EDGE C2 are equivalent in terms of "Network access" (i.e., access to other subjects and websites) and the change was due to the organization structure (i.e., from a well-defined organization to an organization without pre-defined roles) and the allocation of decision rights (i.e., fully distributed). Note that both organizations succeeded in making most information accessible to all members (Manso and B. Manso 2010). Yet, for the EDGE organization, subjects displayed a significant increase in activity during the game (see 'Effort spent' below) and were able to reach the best scores for CSSync.



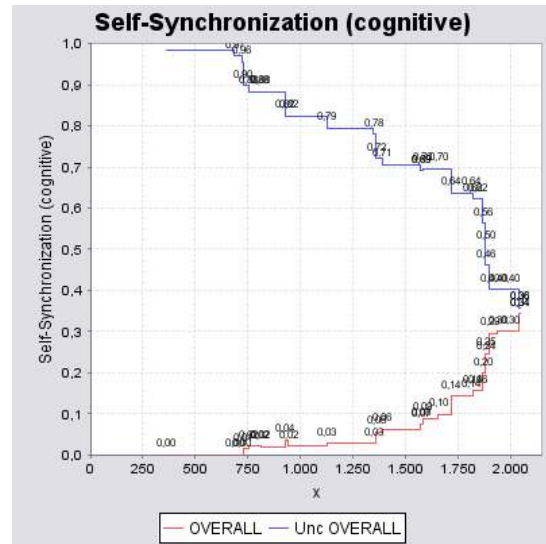
L1-02 Run



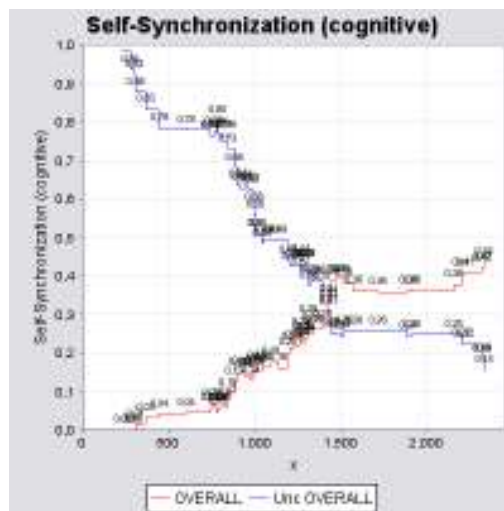
L2-03 Run



L3-04 Run



L4-04 Run



L5-02 Run

Figure 5 – Evolution of CSSync (in RED) and its uncertainty parcel (in BLUE) in time per C2 Approach

Based on the ELICIT experimentations (which are limited to information sharing, awareness and problem solving), the enablers and inhibitors for each C2 Approach affecting CSSync are presented in Table 4.

Category \ CSSync	CSSync Inhibitors	CSSync Enablers
Shared Information Resources	None or a few shared (mainly kept within own entities)	Shared across members. All information accessible across entities.
Patterns of Interactions	Non-existent or highly constrained	Unconstrained / broad and rich across entities and subjects
Allocation of Decision Rights	None / fixed task-role based	Distributed (to all subjects)

Table 4 – CSSync Inhibitors and Enablers

- Q3: *What is the associated cost to Self-Synchronize?*

Additionally, in determining CSSync, the matter of how much it ‘costs’ is also a relevant one. For that, we first will define what we consider as a cost in ELICIT and then make subsequent inferences on the associated CSSync cost.

In ELICIT, we will account as cost the amount of activity (i.e., energy) that a given organization spent during a run. Activity in ELICIT is measured when any of the following actions occurs:

- A factoid is shared by a player.
- A factoid is posted by a player.
- A player performs a pull from a web-site
- A player performs an ID.

Each transaction corresponding to any of the above mentioned activities will be measured as having a unitary activity or energy cost of +1.

The total resulting activity cost (per hour)⁷ measured per C2 Approach is presented in Figure 6.

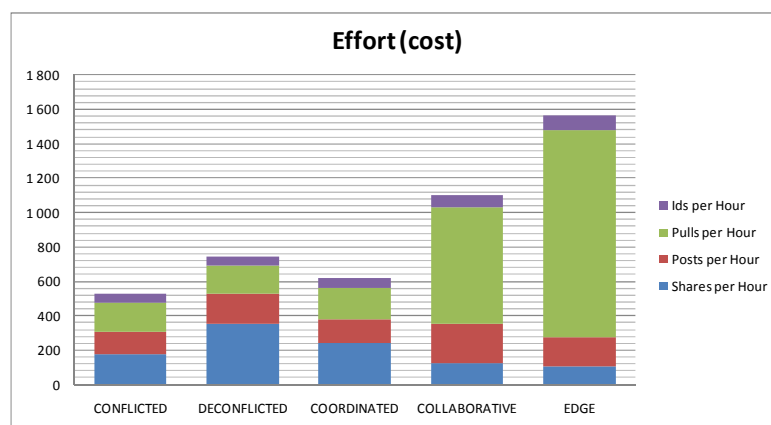


Figure 6 - Effort spent per C2 Approach

⁷ Effort is expressed per hour to normalize the duration of the ELICIT runs to the same value.

EDGE was the C2 Approach that spent the most effort of all, followed by COLLABORATIVE. On the other hand, both CONFLICTED and COORDINATED were the C2 Approaches that spent the least effort. It is also interesting to note that COORDINATED spent less than DE-CONFLICTED albeit it increased in maturity. Operating at a given level of C2 Approach, therefore, has an associated cost.

Additionally, to draw inferences about a possible relation between cost and CSSync we created the plot in Figure 7 with 'effort spent' across the x-axis and 'CSSync' across the y-axis.

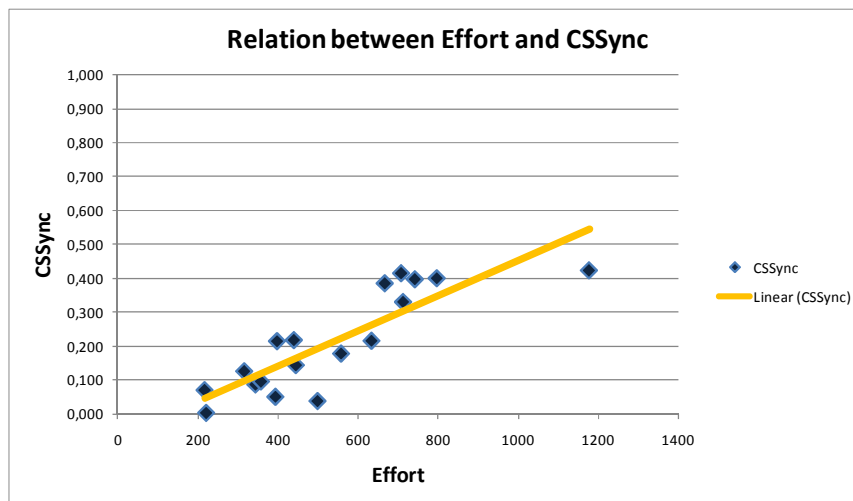


Figure 7 – Relation between CSSync and Effort

We also show in Figure 7 a trendline resulting from applying linear regression to the sequence. From this it is clear that, a direct and proportional relation exists between Effort Spent and CSSync: an increase in Effort corresponding to an increase in CSSync. There seems to exist some outliers (close to the 1000 effort x-axis), but more data is required to draw further conclusions than this. Moreover, we are limited in our analysis to a range between 0.039 and 0.424 for CSSync. It would be worth exploring in future work higher values for CSSync and their implications in terms of effort and C2 Approach adopted.

We conclude that a C2 Approach does influence - as enabler or inhibitor - the emergence of Self-Synchronization and as such has associated costs.

4 SUMMARY, CONCLUSIONS AND FUTURE STEPS

Based on the work by (Manso and B. Manso 2010), we herein further defined the concepts of *Cognitive Self-Synchronization* (CSSync) and *Cognitive Entropy* (CE) now based in Complexity Theory and, more specifically, Kolmogorov Complexity.

We defined CE as a measure of the descriptive complexity of the awareness of a group of individuals – that is, the result of their cognitive process – over time. We defined CSSync as a measure of the degree of self-synchronization – in the cognitive domain – of a group of individuals over time. We normalized CSSync to fit in a scale between 0 and 1 so that its values may have an absolute meaning, for example: 0 means a system is fully disordered; and 1 means a system is fully synchronized.

We further raised pertinent questions about what aspects may influence CSSync and its associated costs. For that, we used existing experimentation data (Manso and B. Manso 2010) to infer that increasing the C2 Approach - that is, (i) increasing the distribution of information, (ii) broadening the patterns of interaction and (iii) distributing the allocation of decision rights across the collective – results in an increase in CSSync as well as 'cost' (i.e., the activity effort).

In Conclusion:

- ELICIT, as an experimentation environment for exploring the implications of different information sharing strategies, has been shown to give important insights for the attack scenario used.
- The results indicate that the ability to self-synchronise in the cognitive domain (as measured by an information theory based measure of merit) shows a steady improvement with the C2 Approach adopted in the game.
- This steady improvement in cognitive self-synchronization with C2 Approach is also directly related to the level of activity (the energy or activity 'cost') required to sustain that C2 Approach.

Future Steps:

The work herein and its conclusions are still preliminary and should be further sustained with more data covering a variety of applications. We consider the following aspects worthy of exploration in future work:

- Increase the experimentation data set and observe values for CSSync beyond 0.5 in order to observe if (and when) the linear relationship between Effort and CSSync is maintained. Moreover, we intend to identify possible non-linear transition points for each C2 Approach.
- Measure CE and CSSync to C2-related experiments using different experimentation platforms, including possibly Dstl's WISE wargame. (Moffat 2003).
- Manipulate additional relevant input variables (see Figure 3). Extend the model to the observation of intermediate variables of interest to CE and CSSync so as to cover multiple levels of complex networks including (i) Base level (network characteristics), (ii) Median Level (intelligent node interactions) and (iii) Top level (NEC Effects) (Moffat 2007).
- Further extend the application of entropy to network-entropy (Lin *et. al.* 2010) and information-entropy (Jin and Liu 2009) and to identify relations between them (i.e., the linkage between network, information, and cognitive entropy). Better understand when low-entropy at lower levels (e.g., organization structure) may not result in low-entropy at higher levels (e.g., cognitive), especially under complex environments.

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5 ANNEX A – INFORMATION ENTROPY AND KOLMOGOROV COMPLEXITY IN THE CONTEXT OF ELICIT⁸

We start by considering the meaning of Entropy in the context of ELICIT. The best approach is that of Kolmogorov Complexity. Given a dataset D , we have a likelihood or probability of D denoted $P(D)$, and then $-\log P(D)$ is the expected description length of dataset D . We have:

$$\begin{aligned} -\log P(D) &= \text{expected description length of dataset } D \\ &= \text{entropy of } D \\ &= \text{Kolmogorov Complexity of } D \end{aligned}$$

More generally:

$$\begin{aligned} -\sum_{i=1}^N p(D_i) \log p(D_i) &= \text{expected description length of the datasets } \{D_1, D_2, \dots, D_N\} \\ &= \text{information entropy of } \{D_1, D_2, \dots, D_N\} \end{aligned}$$

From this equation we can see that:

if $P(D_j) = 1$ for some j and $P(D_i) = 0$ ($i \neq j$), then information entropy has a minimum value of 0, and the expected description length is also zero. Knowledge in this case is a maximum, corresponding to the most succinct description (and corresponding to Gell-Mann's idea of repeated patterns in the data leading to the ability to succinctly describe the data).

If on the other hand, $P(D_i) = \frac{1}{N}$ for all i ($1 \leq i \leq N$) then

$$\text{the expected description length} = -\sum_{i=1}^N \frac{1}{N} \log \frac{1}{N} = \log N$$

Thus the information entropy has a maximum value as does the expected description length and knowledge is a minimum, corresponding to Gell-Mann's idea of a very lengthy description with no pattern.

⁸ The ideas in this section are mainly drawn from (Cover and Thomas 1991).