# Measuring and Modeling Change in $C^3I$ Architectures


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**Citation:** Kathleen M. Carley, Yuqing Ren & David Krackhardt, 2000, "Measuring and Modeling Change in $C^3I$ Architecture." *In Proceedings of the 2000 Command and Control Research and Technology Symposium*. Conference held in Naval Postgraduate School, Monterey, CA, June 26-28, 2000. Evidence Based Research, Vienna, VA.


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• This paper is part of the A2C2 project directed by Daniel Serfaty, Aptima.This work was supported in part by the Office of Naval Research (ONR), United States Navy Grant No. N00014-97-1-0037 under the direction of Dr. Bill Vaughan, ICES (the Institute for Complex Engineered Systems) , and CASOS (the center for Computational Analysis of Social and Organizational Systems) at CMU.



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C2 Assessment Tools & Metrics

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## Abstract

Measures of the $C^3I$ structure are classified using the PCANSS representation scheme. In PCANSS units are modeled using multi-color networks. Then, given their multi-color representation, a series of $C^3I$ structures are simulated. The ability of these measures to predict performance and adaptivity of these structures is then statistically analyzed. It is found that multi-color and multi-cell measures are better at predicting performance and adaptivity.

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## 1. **Introduction and Motivation**

Decades of research have been spent in an attempt to develop a set of meaningful and predictive measures of the $C^3I$ structure. Recent work characterizes the $C^3I$ structure in terms of personnel, resources, tasks and the relations among them. The PCANSS model is a formalization of this characterization (Carley and Krackhardt, 1999). The PCANSS representation scheme provides a network based unifying scheme for categorizing, contrasting and comparing measures of the $C^3I$ structure (Carley and Krackhardt, 1999). $C^3I$ structures, whether they from actual units, lab studies, or computer simulations can be characterized in PCANSS terms and analyzed using the network measures. In other words, using PCANSS it is possible to determine the comparability of measures in lab, field, live-simulation, and computer simulation data gathering exercises and to organize the results of such measurements in a logical framework. In this paper, we take a selection of measures that span the PCANSS space, and examine their robustness, extensibility to different size groups, and ability to predict or capture change in the units $C^3I$ structure. These measures are examined using a set of $C^3I$ structures that vary in their initial attributes (such as size and authority relations). Then using two different simulation models, ORGAHEAD and ORGMEM, the performance of organizations structured in this way is simulated, and the memory of the personnel in these organizations and the possible changes in these structures is simulated. Using ORGAHEAD the set of structures that are most likely to emerge out of the initial structure are generated, given reasonable and veridical assumptions about how units change naturally and in response to stress such as change in workload and attrition. Using ORGMEM the implications of the structure for transactive memory and organizational communication are generated, given information about the nature of human cognition and limits to communicative ability. Results from these simulations are then combined to create a single picture of the degree of similarity/difference in the various measures, there relative ability to predict performance, and their relative ability to predict adaptability.

## 2. **PCANSS Representation of $C^3I$ Structure**

Using the PCANSS formalism we mathematically represent the $C^3I$ architecture as a set of matrices linking personnel, resources, and tasks. In figure 1, we show the equivalent graph and matrix representation of a simple $C^3I$ architecture. The 6 matrices shown in Figure 1 are: precedence (TxT), capabilities (PxR), assignments (PxT), networks (PxP), needs (RxT), and substitutes (RxR).

For each of the PCANSS matrices, measures of the $C^3I$ structure exist – such as span of control, complexity, and redundancy. In fact there are a large number of such measures. Most measures are for “square” or mxm matrices such as precedence, substitutes, and networks. There are also measures for the “rectangular” or mxn matrices such as capabilities, assignments, and needs. For each matrix, and for the structure as a whole, we have selected a set of measures that have been used by other researchers to capture important attributes of the $C^3I$ architecture. Measures used include: span of control, substitutability, centrality, and task complexity.

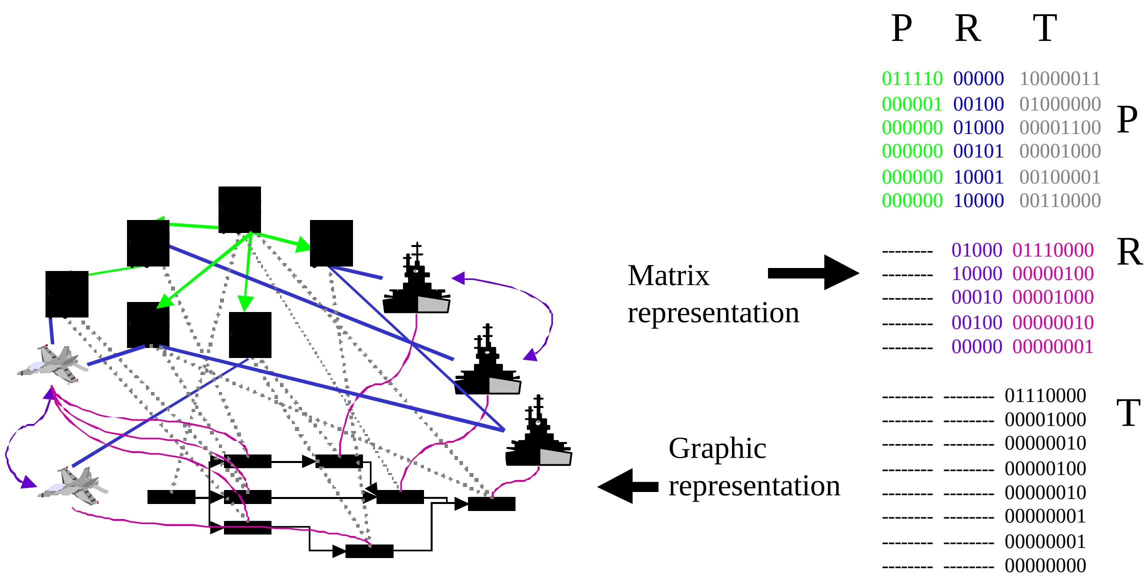



Figure 1: Illustrative $C^3I$ structure in graphic and matrix form

The overall PCANSS matrix is a multi-color network. Personnel, resources and tasks are nodes, each of a different color or type. The overall network, as it links nodes of different colors, is thus a multi-color network. This network is nxn and so most standard network measures can be used; however, doing so violates the implicit assumption of uniformity of meaning across relations. One consequence is that new interpretations of standard measures need to be developed when they are used on multi-color networks. Another implication is that new measures that utilize multiple sub-matrices need to be developed.

Unfortunately, within both the organization and the network literature there are few measures that cross the boundaries and use more than one of the sub-matrices within PCANSS. Building off of the work of Galbraith, Thompson, and the work in cognitive science, a variety of such measures can be constructed. An example of such a measure is need for communication. Another is cognitive load.

Based on the network literature, organization literature, and cognitive science a set of network based measures were identified or constructed. These measures were chosen because a) they are commonly used, b) they enable a logical measurement of the sub-matrices, or c) they use a wider number of sub-matrices or a different combination of sub-matrices. In addition, each of these measures is arguably a predictor of organizational performance or adaptivity. Overall, this generated a set of 19 measures which cover the set of sub-matrices in the PCANSS matrix for which there is variation in the sample set of organizations. This set is described in table 1. In Table 1 the number of stars (*) represents the number of sub-matrices one measurement involves. For example, ****cognitive load means that the calculation of this measure involves four sub-matrices.

| | Individual | Resource | Task |
|---|---|---|---|
| Individual | *Size<br>*Level<br>*Span of control<br>*Network Density<br>*Conductivity<br>*Degree Centralization<br>*Betweenness Centralization<br>*Connectivity<br>*Efficiency<br>*Least Upper Boundedness<br>****Cognitive load | *Consensus<br>*Resource Specialization<br>*Access Redundancy<br>***Need for negotiation<br>****Cognitive load | *Workload<br>*Assignment Complexity<br>***Need for Negotiation<br>****Cognitive load |
| Resources | | | ***Need for negotiation<br>****Cognitive load |
| Task | | | |

**Table. 1 Group Level Measurements**

It should be recognized that any measure used for a sub-matrix on the diagonal (the mxm matrices) such as those for the network cell, can be used for all mxm matrices – just the interpretation changes. Similarly, any measure used in a sub-matrix on the off-diagonal (the mxn matrices) such as those for the assignment cell, can be used for all mxn matrices with suitable changes in interpretation. Finally, measures such need for negotiation and cognitive load, are multi-cell measures and require matrix operations involving multiple sub-matrices.

## 2.1 **Evolving $C^3I$ Structures**

Over time, teams, groups, and organizations change. This change is reflected in alterations in their $C^3I$ structure. This can occur as nodes are dropped or added (changes in the collection of personnel, resources and tasks) and/or relations are added or dropped. Each $C^3I$ unit has a change path. The change path is defined as the set of PCANSS matrices for the unit at each point in time. For an actual military unit, capturing this structure continuously may be prohibitively expensive. Rather, it may be more practical to capture the PCANNS matrices for the $C^3I$ structure at critical or periodic junctures – such as every 6 months. In this study, we are using simulation. Nevertheless, the vast quantities of data that are generated have led us to sample the change path periodically.

## 2.2 **Performance**

The units are performing tasks. Units with different $C^3I$ structures are expected to have different profiles. There are many facets of performance. Herein we consider six measures of performance. The first three are generated by ORGAHEAD (Carley and Svoboda, 1996) and speak to the decision making accuracy of the unit – Overall Accuracy, Sustainability, and Recent Accuracy. Overall accuracy is the percentage of correct decisions made – all 25 tasks for all time periods. Sustainability is the standard error in accuracy given all decisions ever made. The lower the value the more sustainable the overall accuracy level. Finally, recent accuracy is the percentage of correct decisions for the 12 tasks done during each of the last 500 time periods.

The last three measures of performance were gathered using ORGMEM. ORGMEM is a new simulation engine developed to examine how the organizational memory implications of $C^3I$ structures used in and generated by ORGAHEAD, or gathered from experiments or field studies. The first measure is Common Operational Picture – or in other words, what fraction of the information is shared by everyone. The second measure is Cognitive Accuracy; i.e., averaged across everyone what fraction of their perceptions about who knows who and who knows what accurate. Finally, Subjective Accuracy is the fraction of decisions made correctly. ORGMEM and ORGAHEAD use the same type of task to calculate accuracy – a binary choice task. However, the specific sub-tasks (particular binary strings) used in the two cases is different. Further, in ORGAHEAD the personnel make decisions based solely on their task knowledge (what the know and the decisions reported to them by others.) Whereas, in ORGMEM, the personnel make decisions using both task knowledge and their transactive memory of who knows what. Thus the accuracy measures while likely to be correlated are not identical.

Organizations are said to be adaptive if, as they change their $C^3I$ structure, their performance does not suffer. In other words, those organizations where the performance improves or stays the same are considered to be adaptive. To measure adaptivity, performance (as accuracy) is measured for the 250 time periods immediately prior to the organizational change (Pre-Accuracy), the 250 time periods immediately after the change (Post-Accuracy), and for the following 250 time periods (Delayed Accuracy).

## 3. **The Virtual Experiment**

A set of 30 distinct $C^3I$ structures were created (based on the structures examined in Lin, 1994). The 19 measures of structure were then calculated for each of these initial structures. Each structure represents the initial architecture of a different unit. Then the $C^3I$ structure of each of these units was "evolved" using ORGAHEAD and the organizational memory of each of these units was evolved using ORGMEM. Using standard Monte Carlo simulation techniques each unit was simulated multiple times with each of the simulation engines. Basically, these simulation engines are being used to do a series of "what if" analysis, answering the question "what if 'x' happened, then how is the unit likely to change it's $C^3I$ structure?". The scenarios examined differ in the "x" that is happening - structural evolution in ORGAHEAD and social cognition in ORGMEM. These scenarios include: downsizing due to attrition, increased workload, and natural change due to individual learning. For each unit, for each change path, the performance is calculated. Each of the performance measures were calculated for each structure. For Pre, Post and Delayed Accuracy the first five organizational changes and their influence on organizational performance for each of the 30 structures are recorded. Hence, Pre, Post and Delayed are measures on 150 cases. Using this data we examined the usefulness of the measures previously identified for predicting performance and adaptivity.

The univariate statistics for the core measures used in this analysis are described in table 2. The main thing to note is that for the particular structures examined, the range for many of the single sub-matrix measures is relatively small. In general, this range is small for strongly hierarchical structures. Future work should examine structures with less hierarchical structure than those examined herein.

| Variable | N | Mean | Std Dev | Minimum | Maximum |
|---|---|---|---|---|---|
| **Design Measures** | | | | | |
| **Mxm measures** | | | | | |
| Size | 30 | 11.60 | 1.77 | 9.00 | 13.00 |
| Level | 30 | 2.40 | 0.81 | 1.00 | 3.00 |
| Span of Control | 30 | 0.96 | 0.56 | 0.00 | 1.62 |
| Network Density | 30 | 0.17 | 0.03 | 0.11 | 0.20 |
| Conductivity | 30 | 0.00 | 0.004 | 0.00 | 0.01 |
| Degree Centralization | 30 | 0.38 | 0.34 | 0.00 | 1.00 |
| Betweenness Centralizatio | 30 | 0.01 | 0.01 | 0.00 | 0.02 |
| Connectivity | 30 | 0.89 | 0.29 | 0.06 | 1.00 |
| Efficiency | 30 | 0.79 | 0.50 | -1.00 | 1.00 |
| Least Upper Boundedness | 30 | 0.67 | 0.52 | -1.00 | 1.00 |
| **Mxn measures** | | | | | |
| Consensus | 30 | 0.81 | 0.09 | 0.67 | 0.92 |
| Work Load | 30 | 1.74 | 0.77 | 0.68 | 3.00 |
| Resource Specialization | 30 | 0.31 | 0.45 | 0.00 | 1.00 |
| Access Redundancy | 30 | 2.19 | 0.89 | 1.00 | 3.00 |
| Assignment Complexity | 30 | 290.00 | 44.34 | 225.00 | 325.00 |
| **Multi-cell measures** | | | | | |
| Need for Negotiation | 30 | 0.43 | 0.05 | 0.36 | 0.49 |
| Cognitive Load | 30 | 0.58 | 0.01 | 0.56 | 0.60 |
| **Performance Measures** | | | | | |
| Common Operational Pictu | 30 | 20.61 | 3.18 | 15.80 | 26.20 |
| Cognitive Accuracy | 30 | 0.49 | 0.02 | 0.46 | 0.53 |
| Expected Accuracy | 30 | 0.85 | 0.07 | 0.72 | 0.98 |
| Accuracy | 30 | 45.87 | 13.50 | 24.00 | 80.00 |
| Sustainability | 30 | 9.56 | 6.62 | 0.00 | 20.83 |
| Relative Accuracy | 30 | 48.78 | 17.75 | 25.00 | 88.33 |
| Pre Accuracy | 150 | 84.05 | 7.43 | 3.00 | 100.00 |
| Post Accuracy | 150 | 82.26 | 7.99 | 50.00 | 97.60 |
| Delayed Accuracy | 150 | 83.33 | 7.70 | 47.20 | 97.60 |

**Table 2: Univariate Statistics**

## 4. **Designing for Performance and Adaptivity**

Performance, in terms of change in cognitive orientation — common operational picture, cognitive accuracy, subjective accuracy — are strongly related to the number and types of ties in the off-diagonal or mxn sub-matrices in table 1. Note that assignment complexity, which is the least related mxn measure, considers only the potential ties (number of personnel times number of tasks) whereas, the other measures look at actual ties. Multi-cell measures are also reasonable predictors of common operational picture and cognitive accuracy. See table 3 where the correlations between performance measures and design measures are displayed. The six strongest correlations for each performance metric are highlighted in bold.

| | Common Picture | Cognitive Accuracy | Subjective Accuracy | Overall Accuracy | Sustainability | Relative Accuracy |
|---|---|---|---|---|---|---|
| **Mxm measures** | | | | | | |
| Size | -0.0639 | -0.0347 | 0.2261 | -0.3940 | -0.2273 | **-0.3247** |
| Level | 0.0059 | -0.1021 | 0.2308 | **-0.5223** | -0.2287 | **-0.3749** |
| Span of Control | 0.1066 | -0.1985 | 0.1066 | **-0.6243** | -0.1795 | **-0.3335** |
| Network Density | 0.2332 | -0.2972 | 0.0218 | **-0.7101** | -0.1124 | **-0.3025** |
| Conductivity | -0.0633 | -0.0348 | 0.1001 | -0.3164 | -0.1787 | -0.2161 |
| Degree Centralization | 0.3268 | -0.3190 | -0.0185 | **-0.5895** | 0.0040 | -0.2067 |
| Betweenness Centralization | -0.1186 | 0.0216 | 0.2139 | -0.2747 | -0.2178 | -0.2717 |
| Connectivity | 0.2429 | -0.2906 | 0.2807 | **-0.5546** | -0.2109 | -0.1197 |
| Efficiency | 0.3037 | -0.3961 | 0.3597 | -0.3326 | **-0.2706** | 0.0647 |
| Least Upper Boundedness | 0.2781 | -0.3680 | 0.3318 | -0.4882 | **-0.2829** | -0.1497 |
| **Mxn measures** | | | | | | |
| Consensus | **-0.7616** | **0.8351** | **-0.6192** | -0.1950 | **0.2429** | -0.1250 |
| Work Load | **0.7614** | **-0.8349** | **0.6192** | 0.1951 | -0.2432 | 0.1248 |
| Resource Specialization | **-0.6664** | **0.8714** | **-0.8136** | 0.0933 | **0.3878** | 0.0652 |
| Access Redundancy | **0.8069** | **-0.9238** | **0.7676** | 0.0040 | **-0.3356** | -0.0661 |
| Assignment Complexity | -0.0639 | -0.0347 | 0.2261 | -0.3940 | -0.2273 | **-0.3247** |
| **Multi-cell measures** | | | | | | |
| Need for Negotiation | **-0.7614** | **0.8367** | **-0.6245** | -0.1910 | **0.2463** | -0.1210 |
| Cognitive Load | **0.6544** | **-0.7557** | **0.3679** | **-0.5656** | -0.2428 | -0.2158 |

**Table 3. Correlations Between Design and Performance Measures**

Unlike the cognitive size, there are no strong predictors of actual performance; i.e., there are no correlations over .8. The best predictor of accuracy is negative density; but even this is only in the .7 range. What these results are suggesting is that the initial design of the $C^3I$ structure influences individual perception and group cognition, but has no direct relation to actual performance. Basically, design by affecting what people know influences the initial accuracy, but since the $C^3I$ structures adapt over time the initial structure bears little relation to performance in the long run.

To gain greater insight into the way in which design influenced adaptivity, we examined the immediate impact of the way in which change in the units $C^3I$ structure influences performance. Basically, we want to answer two questions here. The first one is whether some types of organizational changes are more likely to happen at the beginning period. The second one is whether different types of changes have similar impacts on performance. In ORGAHEAD, there exist two different types of changes ---- personnel change and connections change. Personnel change can be divided into rotating new members into the unit and rotating old members out of the unit. Connection change can be further divided into changes in the authority/communication structure (Re-design) and changes in the assignment/skills structure (Re-task).

The organizational efficiency is recorded both before, after and two periods after the change. In the data set, the influence is coded into four types, as shown in table 4 below. For example, an adaptive change means that the accuracy goes up both immediately after the organizational change (Post-Accuracy is greater than or equal to Pre-Accuracy) and stays up for the next period (Delayed Accuracy is greater than or equal to Pre-Accuracy).

| Change | Post-Accuracy | Delayed Accuracy |
|---|---|---|
| Adaptive | up | up |
| Short Term Adaptive | up | down |
| Dealyed Adaptive | down | up |
| Maladaptive | down | down |

**Table 4. Characterizing Change in Performance After Change in $C^3I$ Structure**

In ORGAHEAD changes are selected only if the CEO thinks they will improve performance in the near term. Hence, the fact that performance goes down initially, means that the CEO is wrong about 55% of the time. However, due to delayed adaptation, only about 17% of the time is the change truly disastrous. Second, in ORGAHEAD the CEO begins as being equally likely to select any of the four types of changes in the $C^3I$ structure. Hence, the fact that re-design and re-task are so rarely used suggests that the CEO gains an expectation early on that changing in this way will diminish performance.

| Change | Rotate Out | Rotate In | Re-Design | Re-Task | Total |
|---|---|---|---|---|---|
| Adaptive | 9 | 17 | 2 | 4 | 32 |
| Short Term Adaptive | 12 | 14 | 2 | 7 | 35 |
| Delayed Adaptive | 15 | 30 | 6 | 6 | 57 |
| Maladaptive | 7 | 12 | 1 | 5 | 25 |
| Total | 43 | 73 | 11 | 22 | 149 |

**Table 5. Impact of Structural Changes**

As with performance, the various measures of design, particularly the mxm measures, are not particularly strong indicators of adaptation. Rather, units in which consensus is low, workload is high, there is redundancy access to resources, the need for negotiation is low and cognitive load is high are more likely to be adaptive. The lower the need for negotiation or the level of consensus the higher the unit's performance and the more likely that any change in structure will be adaptive. However, as the need for negotiation of consensus increases performance drops and adaptivity becomes problematic. On the other hand, high workload and redundancy in access the higher the performance, the more adaptable, and the greater the chance that changes in performance will be sustained (see Figure 2).

| Design | Pre-Accuracy | Post-Accuracy | Delayed Accuracy |
|---|---|---|---|
| **Mxm measures** | | | |
| Size | -0.0820 | -0.0347 | -0.1109 |
| Level | -0.1004 | -0.0057 | -0.0946 |
| Span of Control | -0.0709 | 0.0644 | -0.0368 |
| Network Density | -0.0643 | 0.1270 | 0.0258 |
| Conductivity | -0.0283 | -0.0070 | -0.0780 |
| Degree Centralization | -0.0688 | 0.1460 | 0.0858 |
| Betweenness Centralization | -0.0640 | -0.0570 | -0.1202 |
| Connectivity | -0.1297 | 0.0343 | -0.0416 |
| Efficiency | -0.0727 | 0.0811 | 0.0007 |
| Least Upper Boundedness | -0.0967 | 0.0776 | -0.0190 |
| **Mxn measures** | | | |
| Consensus | -0.2854 | -0.2797 | -0.2500 |
| Work Load | 0.2852 | 0.2794 | 0.2498 |
| Resource Specialization | -0.0766 | -0.1398 | -0.0792 |
| Access Redundancy | 0.2756 | 0.3011 | 0.2359 |
| Assignment Complexity | -0.0820 | -0.0347 | -0.1109 |
| **Multi-cell measures** | | | |
| Need for Negotiation | -0.2829 | -0.2769 | -0.2472 |
| Cognitive Load | 0.1019 | 0.2815 | 0.1681 |

**Table 6. Characterizing Change in Performance After Change in $C^3I$ Structure**

The link between cognitive load and adaptation is complex. Overall cognitive load is negatively related to performance. However, high cognitive load is related to short term adaptation.. Further work need to look for non-linear relations among cognitive load and adaptation.

A more detailed look at the relation between type of change and adaptivity reveals that in general, change does drive performance down, at least initially (see Figure 3). Re-tasking has the overall lowest impact. Whereas, rotating out personnel is the only change that in the long term results in performance improvements.

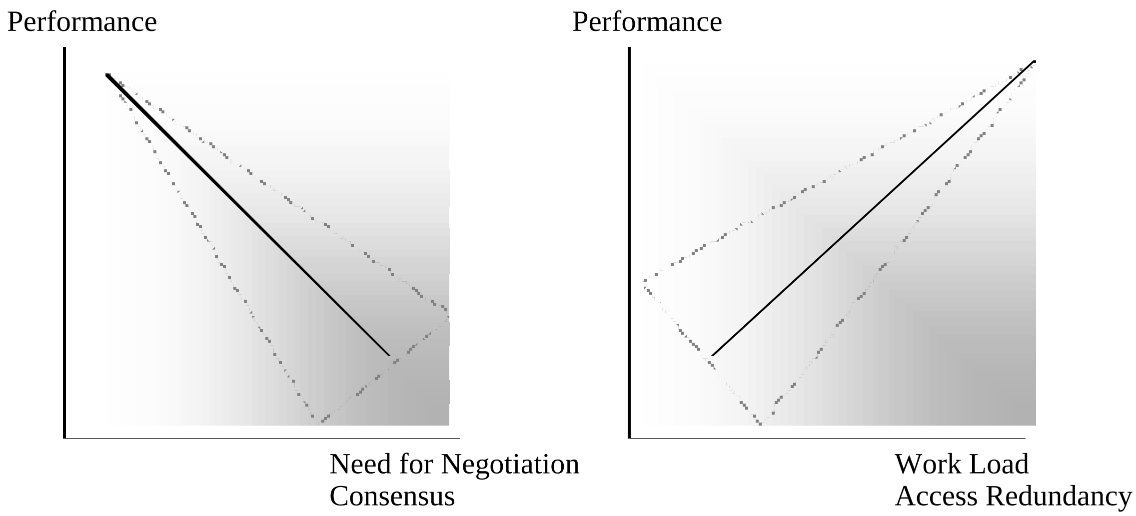
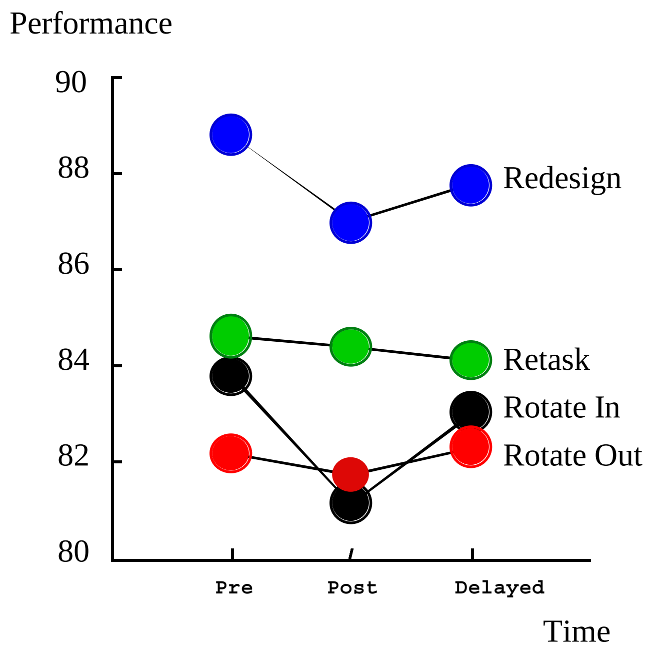



**Figure 2. Stylized description of impact of design on adaptation and performance**

**Figure 3. Impact of Type of Change on Adaptivity**




## 5. **Similarity Among Measures**

To what extent are these various measures capturing radically different information? To address this question the data was factor analyzed. Results suggest, that at least for the $C^3I$ structures examined in this paper, these measures are highly related. Analysis reveals three dominant factors, the first related to complexity in the ties in the network, the second relating to the off-diagonal cells, and the third relating to cognitive load. For these factors, only the third, the cognitive load factor is predictive of adaptation. While cognitive load is negatively related to performance and to pre-change accuracy, it is the best indicator of long terms adaptivity.

## 6. **Summary**

Results indicate that measures that capture information on only one of the 3 components – personnel, resources or tasks — are unable to predict or capture performance or change in a robust fashion. Multi-color measures (that take into account two or more components) and in particular multi-cell measures (that take into account relations across the PCANSS cells, fair better at tracking and capturing change. None of the measures, in isolation, are excellent at predicting actual performance or adaptivity. That is, none have greater than .9 correlation with adaptivity. However, of these measures cognitive load is the best indicator of long terms adaptivity.

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