A Systems Perspective on Mental Models Research
Toward a Shared Understanding of Team Cognition

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From Practice to Theory – and Back Again
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Structure of the Presentation

- Five Approaches to Team Cognition
- Criteria for Classifying the Approaches
- Conclusions and Future Work
Background on Classification of Team Cognition

- Systems engineering is knowledge-driven, so research on team cognition is needed to understand how engineering teams work.

- Several classification schemes proposed previously but often only spanning one or two disciplines:
  - Avnet and Weigel (2013) expanded this classification to include naturalistic decision making (NDM) and a new network-based approach termed structural.

- These classifications schemes did not address literature on the process of mental model formation (e.g., Sterman, 1994).
Five Approaches to Team Cognition

1. Naturalistic Approach
   - Naturalistic Decision Making (e.g., Klein, 1998)
   - System Dynamics Models of Learning (e.g., Doyle and Ford, 1998)

2. Social Network Analysis of SMMs (e.g., Avnet and Weigel, 2013)

3. Structural Approach

4. Formative Approach

5. Interactive Team Cognition (e.g., Cooke, 2013)

6. Holistic Approach
   - Shared Mental Models (SMMs) (e.g., Mohammed, 2001)

7. Collective Approach
# Summary of the Five Approaches

<table>
<thead>
<tr>
<th>Field or Discipline</th>
<th>Naturalistic</th>
<th>Formative</th>
<th>Collective</th>
<th>Holistic</th>
<th>Structural</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field or Discipline</td>
<td>NDM (human factors)</td>
<td>Systems dynamics and org behavior</td>
<td>Social and org psychology</td>
<td>Human factors</td>
<td>Social network analysis</td>
</tr>
<tr>
<td>Benefits</td>
<td>Real-world emphasis; focus on dynamic settings</td>
<td>Dynamic systems-level view; multiple levels of analysis</td>
<td>Direct metric of cognition; survey data allowing quantitative analysis</td>
<td>Focus on interaction of team members; quantitative analysis</td>
<td>Scalable quantitative metric of cognition; focus on changes over time</td>
</tr>
<tr>
<td>Drawbacks</td>
<td>Lack of quantitative metrics; high research labor cost</td>
<td>Complex data collection; limited base of research</td>
<td>Assumption of knowledge homogeneity; measurement outside of team context</td>
<td>Assumption that team cognition and interaction are equivalent</td>
<td>Measurement outside of team context; no means to explain change over time</td>
</tr>
</tbody>
</table>
Structure of the Presentation

• Five Approaches to Team Cognition

• Criteria for Classifying the Approaches

• Conclusions and Future Work
Several criteria were defined to classify approaches

- **Research Setting**
  - Field or laboratory
- **Team Size**
  - Ranging from individual to large organizations
- **Methodology**
  - Various quantitative and qualitative techniques
- **Time Dependence**
  - Dynamic or static constructs
- **Knowledge Distribution**
  - Homogenous or heterogeneous
Research Setting

NDM focuses on real-world decision makers in the field under high time pressure

Quantitative research tends to focus on controlled lab-based studies with small teams

Source: http://ih1.redbubble.net/image.11947694.7153/flat,550x550,075,f.jpg

Source: http://i.bnet.com/blogs/cockpit-sim-pilot-copilot-hr.jpg
Team Size

Dyads - do not experience peer influence but more likely to result in stalemate

Triads - more likely to be influenced by peers but unlikely to have cliques

Collective and holistic approaches

Formative and structural approaches - very large teams and organizations
Methodology

Qualitative

- Direct ethnographic observations to examine phenomena in their natural context without making a premature attempt to narrow focus
- Analysis of communication by using techniques such as semantic analysis, keyword indexing, content coding and word count analysis
- Survey-based measurement of individuals which can then be quantitatively adapted to teams

Quantitative
Time Dependence

Naturalistic Decision-Making

Source: http://ih1.redbubble.net/image.11947694.7153/flat,550x550,075,f.jpg

Mental Model Formation

Adapted from Sterman (1994)

Interactive Team Cognition

Source: http://i.bnet.com/blogs/cockpit-sim-pilot-copilot-hr.jpg

Structure of Shared Knowledge

Adapted from Avnet and Weigel (2013)
Teams…“Can vary in the degree to which their knowledge is distributed, with very specialized teams having little cognitive overlap among members, and less specialized teams having more cognitive redundancy” (Kiekel and Cooke 2004)
# Distinguishing Attributes of Approaches to Team Cognition

<table>
<thead>
<tr>
<th>Approach</th>
<th>Research Setting</th>
<th>Team Size</th>
<th>Methodology</th>
<th>Time Dependence</th>
<th>Knowledge Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naturalistic</td>
<td>Field</td>
<td>Focus on individual but any size</td>
<td>Ethnographic observation</td>
<td>Fundamental</td>
<td>Homogeneous</td>
</tr>
<tr>
<td>Formative</td>
<td>Field</td>
<td>Individual to organization</td>
<td>Interviews and system dynamics modeling</td>
<td>Nonlinear and evolutionary</td>
<td>Depends on team size</td>
</tr>
<tr>
<td>Collective</td>
<td>Usually laboratory</td>
<td>Dyads or small teams</td>
<td>Analysis of overlapping survey responses</td>
<td>Static</td>
<td>Homogenous</td>
</tr>
<tr>
<td>Holistic</td>
<td>Usually laboratory</td>
<td>Dyads or small teams</td>
<td>Quantitative textual analysis</td>
<td>Dynamic team interaction</td>
<td>Heterogeneous</td>
</tr>
<tr>
<td>Structural</td>
<td>Field</td>
<td>Teams and organizations</td>
<td>Network analysis of SMMs</td>
<td>Change in structure</td>
<td>Inherently heterogeneous</td>
</tr>
</tbody>
</table>
Structure of the Presentation

• Five Approaches to Team Cognition

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• Conclusions and Future Work
Summary and Conclusion

• Teams have an important place in a world of complex socio-technical systems that are built, operated, and supported by large teams and organizations

• Team cognition will play a critical role in research on these systems in the coming years

• The classification scheme presented here lays the groundwork for a comprehensive understanding of the ways in which team cognition can be studied depending on the particular context
Next Steps in Team Cognition Research

• Systematic literature review to refine the classification scheme

• Team cognition in emergency response
  – Study with the Emergency Operations Training Center (EOTC) operated by the Texas A&M Engineering Extension Service (TEEX)

• Network Analysis of Safety Culture
  – Ongoing study applying the structural approach with the Texas A&M Mary Kay O’Connor Process Safety Center (MKOPSC), safety culture consultancy Sentis, and others

EOTC Simulation Exercise in Progress. *Source:* Texas A&M Engineering Extension Service
Directions for Future Work

• Future work should focus on building a theoretical basis for analysis of team cognition in systems engineering teams

• Planned interdisciplinary conferences on team cognition will enable open dialogue, invite critique, and enable researchers to understand the flaws of each approach

• Analysis to include related theories, such as team situational awareness (TSA) and transactive memory systems (TMS)
  – Reviews including these approaches have been done (e.g., Wildman et al. 2014)

• In the longer term, empirical studies comparing the usefulness of the approaches in various settings are needed
Thank you
References (1/2)


Avnet, MS, & Weigel AL. *The Structural Approach to Shared Knowledge: An Application to Engineering Design Teams*. Hum fac erg soc 2013;


References (2/2)


Backup
Naturalistic Approach

- Based on naturalistic decision making, pioneered by Gary Klein, that was designed to understand expert decision making in real-world situations usually under extreme time pressure.
- Research in the filed predominantly use ethnographic techniques to study teams in context.
- Postulates the presence of a team mind with features similar to the mind of an individual such as limited working memory, parallel information processing and self-monitoring.
- Drawbacks include:
  - Too narrowly focused on a specific team setting (e.g. military).
  - Has high expense, intense labor and tremendous commitment from sponsors, users, researchers and managers.
- Become a platform for the study of macro cognition.
Formative Approach

- Principally applied in research that is at the intersection of the fields of organizational behavior and systems science.
- Generally used to demonstrate conceptually how a decision-maker’s environment shapes his/her mental model while that mental model influences decisions, which, in turn, affect the environment.
- When considering individual cognition, the nodes depict ideas and the arrows represent the learning process through which ideas are altered.
- From an organizational standpoint, the nodes represent individuals and other elements of the surrounding environment that shape the mental models of all individuals involved and, as result, the process of learning in the organization.
Collective Approach

• The collective approach is based on studies conducted primarily by researchers in the fields of social and organizational psychology.

• Key features of this approach are:
  – Survey-based technique involving interviewing individual team members.
  – The overlap in cognition between different team members is then computed.
  – In teams of more than two members, the pairwise ratings are then averaged to obtain the overall team cognition.

• The nodes represent team members and the + sign indicates that overall team cognition is based on simple sum of all pairwise SMM.

• Assumes that knowledge is homogenously distributed across team members.
Holistic Approach

- The holistic approach is based on research done in the field of human factors.
- It extends the definition of cognition much beyond a single individual to include other members.
- The key characteristic of holistic approach is that researchers focus on observed interactions among team members in a well-defined laboratory setting.
- They elicit relatedness ratings in the form of answers to questions about the work performed from the team as a whole.
- The relatedness rating obtained is subject to the same analytic process as individual with the result assumed to reflect the team’s mental model.
Structural Approach

- The structural approach is based on the nascent body of literature that lies at the cross section of the fields of social and organizational psychology and network science.
- Broniatowski and Magee (2012) extracted social networks from transcripts of expert committee meetings based upon Bayesian clustering.
- Using the above, a metric of change in shared knowledge can be computed at different points in time to determine team learning.
- Expanding above research, Avnet and Weigel (2012) devised a method to construct networks of shared mental models to exhibit the structure of shared knowledge.
- In the structural approach, team cognition is represented as a social network where each node represents a person and each edge a measure of shared cognition (e.g., an SMM) between two people.
Perception of Complexity in Design

2016 Conference on Systems Engineering Research: Huntsville, AL

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Stevens Institute of Technology
Effort Overruns in Large-scale Engineering Projects

• 20-40% overruns on cost and schedule are common
• 100% overruns are not uncommon
• Cross-domain: defense acquisition, Earth and space science, software, infrastructure and public works
• Delusion or deception? (Flyvbjerg et al. 2009)
• What are human limitations to perception in design (complexity)?

F-35 Lightning II (Joint Strike Fighter)

James Webb Space Telescope
Model of Complexity in Design

\[ P(t) = P_0 \exp(r_P t) \] : Exponential performance growth

Shown in technology studies (popularized in Moore’s Law)

25-40\% annual growth rates in info. tech. \textit{(Koh and Magee 2006)}

2-15\% annual growth rates in energy tech. \textit{(Koh and Magee 2008)}
Model of Complexity in Design

\[ E(P) = E_0 P^{kp} : \text{Desired performance} \rightarrow \text{required effort} \]

Extended “S-curve” model with multiple architectures (Christensen 1992)
Mathematical form selected for convenience
Conflates descriptive and perceived sources of effort
Model of Complexity in Design

\[ C(P) \geq C_0 P^{k_C} : \text{Desired performance } \rightarrow \text{ min. complexity} \]

Complex designs can achieve higher performance
Complexity is necessary but not sufficient (e.g. Rube Goldberg)
\( k_C \) : growth factor based on design domain (descriptive)
Model of Complexity in Design

\[ E(C) \geq E_0 C^{k_E} : \text{Complexity} \rightarrow \text{min. required effort} \]

Complex designs require more design effort

Effort is necessary but not sufficient (e.g. unproductive work)

\[ k_E : \text{growth factor based on design context (perceived)} \]

\[ \log E \rightarrow \log C \]

\[ k_E \geq 1 \]
Model of Complexity in Design

\[ C(P) \geq C_0 P^{k_C} \]

\[ P(t) = P_0 \exp(r_P t) \]

Excess complexity

Excess effort

\[ E(C) \geq E_0 C^{k_E} \]

\[ E(t) \geq E_0'' \exp(r_P k_C k_E t) \]
Measuring Perception of Complexity

Validate $E(C) \propto C^{k_E}$ functional form and measure $k_E$ using secondary data: (Grogan and de Weck 2016)

- Find $N$ DPs to meet $N$ FRs (coupled or uncoupled)
- $N$ DPs and FRs distributed among $n$ designers
- Vary $N$, $n$, DP-FR coupling
- Measure completion time $\tau$
- 30 individuals, 10 teams, 374 total data points
Measuring Perception of Complexity

\[ C(P) \approx C(N) = C_0 N^{k_C} \]

\[ C_0 = 1 \]

\[ k_C = 1 \text{ (Uncoupled)}, \ k_C = 2 \text{ (Coupled)} \]
Measuring Perception of Complexity

\[ \tau(C) = \frac{E(C)}{n} = \frac{E_0}{n} C^{k_E} = (b_0 n^{b_2} O^{b_3} b_4 \varepsilon_{0.1} b_5 \varepsilon_{0.11}) C^{k_E} \]

\[ \log \tau = \beta_{0j} + \beta_{1j} \log C + \beta_{2j} \log n + \beta_{3j} \log O + \beta_{4j} \varepsilon_{0.1} + \beta_{5j} \varepsilon_{0.11} \]

\( \tau \): Task completion time

\( C \): Design complexity (\( N \) or \( N^2 \))

\( n \): Team size

\( O \): Task order (learning effects)

\( \varepsilon_i \): Dummy for target width (default 0.05)
Measuring Perception of Complexity

Multi-level (hierarchical) linear regression

<table>
<thead>
<tr>
<th>Random</th>
<th>Coef.</th>
<th>Step 1 Model (AIC = 665.97)</th>
<th></th>
<th>Step 2 Model (AIC = 641.97)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>$\gamma_{01}$</td>
<td>Factor</td>
<td>Variance</td>
<td>Std. Dev.</td>
<td>Factor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Intercept</td>
<td>0.000</td>
<td>0.000</td>
<td>log $C$</td>
</tr>
<tr>
<td>$G$</td>
<td>$\gamma_{11} (\Delta k_E)$</td>
<td>log $C$</td>
<td>0.018</td>
<td>0.134</td>
<td>0.277</td>
</tr>
<tr>
<td>Intercept</td>
<td>$\gamma_{00}$</td>
<td>1.367</td>
<td>0.119</td>
<td>11.485</td>
<td>1.367</td>
</tr>
<tr>
<td>log $C$</td>
<td>$\gamma_{10} (k_E)$</td>
<td>1.343</td>
<td>0.052</td>
<td>25.865</td>
<td>1.343</td>
</tr>
<tr>
<td>log $n$</td>
<td>$\gamma_{20}$</td>
<td>1.215</td>
<td>0.103</td>
<td>11.824</td>
<td>1.215</td>
</tr>
<tr>
<td>log $O$</td>
<td>$\gamma_{30}$</td>
<td>-0.175</td>
<td>0.034</td>
<td>-5.119</td>
<td>-0.175</td>
</tr>
<tr>
<td>$\epsilon_{0.1}$</td>
<td>$\gamma_{40}$</td>
<td>-0.342</td>
<td>0.114</td>
<td>-2.993</td>
<td>-0.342</td>
</tr>
<tr>
<td>$\epsilon_{0.11}$</td>
<td>$\gamma_{50}$</td>
<td>-0.836</td>
<td>0.153</td>
<td>-5.465</td>
<td>-0.836</td>
</tr>
</tbody>
</table>

$$\tau = 3.83 \cdot C^{1.343} \cdot n^{1.215} \cdot O^{-0.175} \cdot 0.71^{\epsilon_{0.1}} \cdot 0.43^{\epsilon_{0.11}}$$
Measuring Perception of Complexity

- Perception of Complexity $k_{E}(G)$
- Comparison across All Groups, Individuals, and Teams

- Bar graph showing count distribution for Perception of Complexity $k_{E}(G)$
- Different bars indicate Individual and Team categories

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Measuring Perception of Complexity

\[
\tau_2(C) = \frac{C^{k_{E2}}}{C^{k_{E1}}} = C^{k_{E2} - k_{E1}} = C^{\Delta k_E}
\]
Discussion – Limitations

Model of complexity in design

- Partially validated:
  - \( P(t) \propto \exp(r_P t) \): good support
  - \( C(P) \propto P^{k_C} \): no similar widely-accepted complexity metric
  - \( E(C) \propto C^{k_E} \): validated here
  - \( E(t) \propto \exp(r_P k_C k_E t) \): untested

- Simplest form assumes parameters \((r_P, k_C, k_E)\) are time-invariant

- Effort overrun mechanisms are only conjectures at this time

Experimental results

- Simplified parameter design task
  - Controlled experimental conditions, many data points
  - Limited generalizability to real design (context and scale)

- No direct assessment of effort overruns in design tasks
  - Secondary data from prior study
  - Did not record effort estimates
  - Did not order tasks based on complexity/desired performance

Experimental results

- Simplified parameter design task
  - Controlled experimental conditions, many data points
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- No direct assessment of effort overruns in design tasks
  - Secondary data from prior study
  - Did not record effort estimates
  - Did not order tasks based on complexity/desired performance
Conclusion

- Model of complexity in design: \( E(t) \geq E_0'' \exp(r_P k_C k_E t) \)
- Experimental data supports form \( E(C) \propto C^{k_E} \)
- Perception \( k_E \) varies (significantly) in designers
- Differential perception \( \Delta k_E \) among estimators and designers may contribute to “delusion”
- **Future work**: strengthen generalizability, validate effort overrun phenomenon, develop tools to improve perception of complexity
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