A Collaborative Dimensions Framework: Understanding the Mediating Role of Conceptual Visualizations in Collaborative Knowledge Work

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Abstract

Facilitating collaborative knowledge work is a crucial issue in management: knowledge is a key corporate asset, but it is typically spread across various people in different organizational functions. In this paper we explore how conceptual visualizations (such as diagrams, visual metaphors, charts, sketches) can be constructed and used as cognitive artefacts that support collaborative knowledge work. In order to facilitate tasks such as the creation and sharing of knowledge in teams, we propose a collaborative dimensions framework as a tool for understanding how visual artefacts can facilitate collaboration in circumstances that involve distributed knowledge. The framework is based on the widespread Cognitive Dimensions of Notation framework and is enriched with criteria from the boundary object paradigm discussed in organization science. The dimensions of the framework are described and then applied to three different visualizations that are used in collaborative knowledge work. A discussion of future research needs concludes the paper.

1. Introduction

Business meetings are multimodal. Although much collaborative knowledge work consists of verbal exchanges, most meetings in organizational contexts also include shared and distributed visual representations. These range from simple ordered lists such as a meeting agenda, or bullet points on a presentation slide, to complex visualisations of conceptual relations, strategic interactions, data charts or technical designs.

Thus far, there is little support beyond common sense guidelines for choosing which visualisation might be most appropriate in any given context. Most such decisions are driven either by the capabilities of the tools to hand (e.g. Power Point, Excel), or by the habits and preferences of a particular individual, professional community or organisation. In this paper, our goal is to identify the factors that contribute to the choice of an effective visual representation for collaborative knowledge work to support distributed cognition, and to organize them in a conceptual framework. We focus on visualisation as an artefact, rather than on the people who use it. This technical focus allows us to express important decision factors as *dimensions* – properties of a visualization that either facilitate or discourage certain kinds of use. Often there are trade-offs between these dimensions, such that choosing a particular kind of visualization will be beneficial for one purpose, while less useful, or even obstructive, for another.

Understanding these decision factors is particularly valuable for meeting leaders, consultants, and any person involved in designing a meeting interaction, when they must choose how to support collaborative knowledge work with visual representations. Such understanding is also likely to be of value to researchers and product developers who create novel visualisation support tools.

In particular, it is beneficial for such facilitators and tool developers to understand the existence of trade-offs between dimensions. This is in contrast to the frequent advocacy of design "guidelines" that are presented as universal attributes of a good visualisation. We show that the best designs are likely to result from selecting a combination of dimensions that are best suited to a particular type of collaborative activity, and that should therefore be prioritised in that situation, rather than a "checklist" approach that focuses on satisfying an absolute set of quality criteria.

2. Methodology

Our findings are derived firstly from the analysis of research literature on visualisation and collaboration, and secondly from a combination of expert panels and exploratory interviews with reflective practitioners who routinely employ visualisations in collaborative business contexts. The structure of the paper reflects these two sources, followed by the presentation of a design framework that takes both into account.

2.1 Literature review

We focus on reviewing three main fields that are particularly relevant to provide the theoretical foundation of this work: (i) the Cognitive Dimensions framework on notations, especially as applied in the context of research on diagrammatic reasoning and design, (ii) research into the function of boundary objects, in the context of organization science, and (iii) the general scientific discourse on information and knowledge visualization.

One starting point for this review is the Cognitive Dimensions of Notations framework, originally proposed by Thomas Green [9]. As an applied cognitive psychologist who had spent many years investigating the usability properties of visual notations, Green discovered that it was seldom possible to cite specific experimental results offering direct guidance with respect to the design of new notations. It would be possible to conduct experiments to test each proposed feature, but this would be far too expensive. However, as an alternative, it was possible to identify some general design principles, based on prior research that indicated likely problems that might arise in a new design. With collaborators including Petre [10] and Blackwell [1], Green identified a number of such properties that were collectively described as *Cognitive Dimensions*, and could be used as a “discussion vocabulary” by designers wishing to clarify and evaluate their design options. A textbook introduction to the Cognitive Dimensions framework can be found in Blackwell & Green [2]. The Cognitive Dimensions framework describes the way that designers can anticipate certain kinds of activity, such as modification or exploratory design, by creating notational systems whose dimensional profile is particularly well suited to those activities.

A more explicit focus on social context of notation use is provided by Hundhausen’s [12] communicative dimensions of notations, which is derived from observations of instructional and education contexts, where visualisations are presented as communicative aids. In these contexts, new dimensions become important, for example in the extent to which a notational choice might either encourage or discourage narrative presentation, or support reference to specific elements of a visualisation.

Research into the function of boundary objects focuses on knowledge transfer and its integration into organizational and design practice. Star and Griesemer [17] considered the characteristics that boundary objects should have to be able to bridge knowledge across different organizational functions or divisions. Those theories attracted the interest of a number of authors in different fields, including the work of Carlile [5] in management and of Ewenstein and Whyte [7] in architecture. Their findings show that, through the use of boundary objects, people from different areas of expertise can bridge their separate knowledge domains, create a shared understanding, and improve decision making.

Boundary object research shares the same goal as the research that we propose here, however, analytic descriptions of visual boundary objects or ad-hoc creation of boundary object visualizations have thus far attracted limited attention - with a few exceptions, such as the work of Gasson [8] on Soft Systems Methodology for eliciting implicit knowledge. The cognitive and communicative dimension frameworks have not previously been applied to collaborative visualizations in organizations. We thus wish to combine these two approaches in order to create a formal tool for the description of visualization used as knowledge-work catalyst device.

Thirdly we analyzed the literature on visualization technologies, in particular the information visualization work of Shneiderman [16] and Karabeg [13], and that on knowledge visualization by Eppler [6] and Suthers [18]. Information visualization differs from knowledge visualization with respect to the object that is visualized — information visualization refers mainly to quantitative data visualization, while knowledge visualization usually relates to the externalization through visualization of people’s insights, opinions, assessments, experiences or perspectives. The boundary between the two disciplines is not always easily drawn, and the intersection is rather large. In the discourse on representations an insightful work from a different perspective (logic) was conducted by Shimojima [15] who investigated the match of information presentation modes and reasoning efficacy.

2.2 Interviews and expert panels

For the empirical part of our work, we conducted twelve exploratory semi-structured interviews, two expert panels and two naming tests. In detail, we interviewed four freelance consultants who make extensive and innovative use of visualization in their daily work, three end-users of a business visualization tool, a consultant from a multinational consulting company and four academics, expert respectively in cognitive dimensions (T. Green), diagrams (N. Crilly), roadmapping (R. Phaal) and strategic decision making (M. Sobotka).

Iinterviews were conducted in both Switzerland and the UK. The end-user interviews were conducted by phone and lasted around 20 minutes. The multinational consulting company was approached both though emails and phone interview. Finally consultants and academics were interviewed in person for one and a half to two hours: they were asked to describe a typical scenario of interaction with diagrams, to describe how they choose which visualization is appropriate for which task, and to identify some positive and negative characteristics of visualizations for collaborative work. The interviews were reviewed and analyzed by listening to the recorded material and annotating the main topics they brought to light, the elements of confirmation and the recurrence of some relevant issues. From these exploratory interviews, a number of relevant issues have emerged regarding the effect of different kinds of visualization on group interaction and collaboration.

Further insights were gained through two expert panels. The first addressed the specific topics of dimension naming, with three cognitive dimensions experts. The second reviewed diagram characteristics (advantages, disadvantages, diagram-task matching) with fifteen researchers from different departments of the University of Cambridge who have interests or specialize in the use of diagrams. We also conducted two exploratory observations of group knowledge work: a roadmapping workshop (using mainly posters with post-its) involving 10 managers, and a strategy consultation with three top managers (using mainly poster matrixes and let's focus software), both in the UK.

During the framework creation process we iteratively addressed the problem of naming clarity, conducting two different naming tests with 15 participants each (native speakers of English, German, Italian, Japanese, Arabic, and Serbo-Croatian). In the first test, conducted at the University of Cambridge, we provided only the provisional names of the dimensions, and asked the participants to write what they thought were the definitions for these terms. The problems and suggestions that emerged from this test were addressed and a pool of new dimension names were created. The second test was conducted at the University of Lugano, Switzerland: the participants were given a brief definition and a choice of four names for each dimension, from which they had to choose the most suitable one.

The final aim of our research is to provide an easy-to-use and reliable method to evaluate collaborative dimensions, in order to be able to choose the appropriate visual formalism for any collaborative task. Based on the literature review and empirical work above, we propose a collaborative dimensions framework in the next section, and provide some example applications in section 4.

3. Collaborative Dimensions Framework

After collecting a numerous and varied set of dimensions from the literature, we aggregated and classified them, grouping together similar concepts and eliminating redundancies. The full list that emerged, previously discussed in more detail in [4], was too large to be of any use for simplifying and understanding how diagrams can support collaborative knowledge work. Therefore, we decided to have a limited number of dimensions in order to have a broad-brush tool that can be easily understood, manipulated and applied by non-experts in organizational collaborative knowledge work. To prioritize, reduce and classify the dimensions we used two main principles: the number of times a concept emerged from the literature and the evidence that emerged from our interviews. We constructed a schema in three sections (cognitive, communicative and collaborative macro-dimensions) that we used as a tool to support the task of aggregating literature dimensions and evidence from the interviews, grouping together similar concepts. In Figure 1 we show the aggregation of concepts with reference to the dimensions from the literature review.

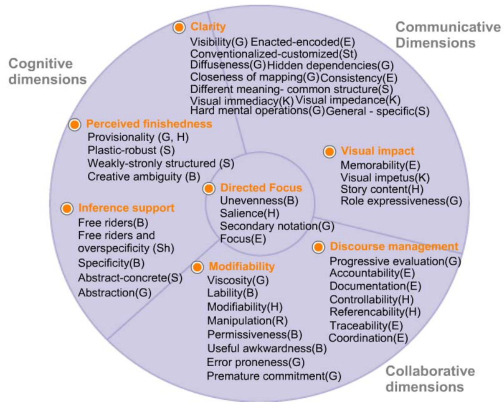

Figure 1. Dimensions classification

The analysis of interview findings in the light of this classification, refined via expert panels, is a 7-dimensional radar graph, expressing the *collaborative dimensions framework* (Figure 2) according to which diagrams can be rated, and which can supply group knowledge-work designers or facilitators with a common vocabulary and design heuristics for their work. The dimensions of this framework are: visual impact, clarity, perceived finishedness, directed focus, inference support, modifiability and discourse management.

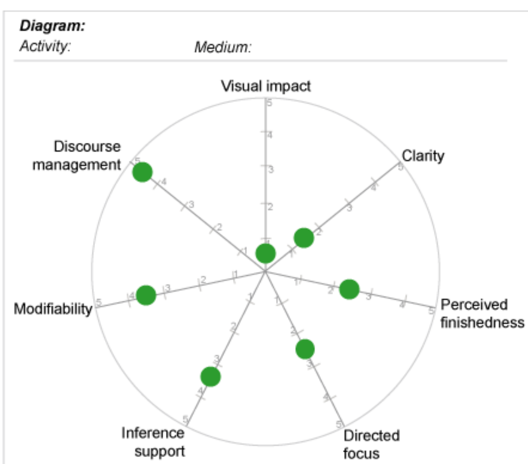

Figure 2. The collaborative framework

Our collaborative dimensions framework refines and extends Hundhausen's [12] communication dimensions framework, which in turn is based on Green's cognitive dimension framework [9]. We can consider the cognitive, communicative and collaborative perspectives as subsequent steps: cognitive support is necessary for communication support, which is necessary for collaboration. In detail, by comparison to Hundhausen's work, the dimensions *Modifiability* and *Provisionality* remain the same, although we renamed the second *Perceived finishedness* because our comprehension tests showed that no diagram experts (unless familiar with Green's framework) could explain the meaning of the word Provisionality. We re-conceptualized the other dimensions proposed by Hundhausen, including them under the umbrella of other dimensions: we incorporated *salience* into *directed focus*, *story content* into *visual impact*, *controllability* and *referencability* into *discourse tracking*.

We believe that these seven dimensions are on the same level of granularity and as orthogonal as possible with respect to each other, as suggested by Blackwell's guidelines [1] for creating new descriptive dimensions.

To better explain these dimensions and assess their utility in understanding differences among collaborative visualisations, we apply them to three visualisations in section 4. It is important to note that we do not claim that the best diagram will be the one with the highest score on all dimensions: an essential insight of Green's original framework is that the importance of each dimension changes with regard to different tasks. Therefore, the optimal combination of ratings on the different dimensions may change radically with different activity types, for example in the distinctive activities of idea generation, evaluation, analysis or planning.

3.1 Detailed Definition of the Dimensions

We now provide detailed definitions of each collaborative dimension, including its relationship to concepts from the literature review, and empirical support from our interviews in the form of verbatim quotes.

3.1.1 Visual impact

Definition: Extent to which the diagram is attractive and is facilitating attention and recall.

Similar dimensions in literature: Visual impetus in Karabeg [13]: "How attractive and inviting to action and further exploration is a visualization".

It relates to the visual characteristics of a diagram, including the stylistic sophistication, the story content [12] the role expressiveness [9] of the whole graphic or of the parts, including elements such as icons, color scheme, visual conventions and attention grabbers. A pleasurable visualization is more likely to attract the attention of the viewer and create a positive halo effect on the other aspects of the visualization, but the downside is that it is not necessarily essential and can even be distracting. Furthermore it lowers the likelihood that the user will perceive the visualization as easily modifiable.

Quote: *"I use cartoons, it's my style: it's fun and people like it"*

3.1.2 Clarity

Definition: property of the diagram to be self-explanatory and easily understandable with reduced cognitive effort

Similar dimensions in literature: Visibility by Green [9]: "Ability to view components easily". Visual immediacy by Karabeg [13]: "The first impression; characteristic that enables the viewer to perceive and recognize "at a glance".

The visibility of a diagram is related to its complexity, the familiarity of the group with it, the method of development (if the diagram is constructed in front of the target group or it is presented to them ready-made), and the consistency of elements in the graph.

Quotes: *"If the diagram is too complicated, people just switch off".*

3.1.3 Perceived finishedness

Definition: characterizes the extent to which the visualization resembles a final, polished product (original definition of provisionality by Hundhausen, [12]).

Similar dimensions in literature: provisionality in Hundhausen [12], provisionality in Green [9]: "Degree of commitment to actions or marks".

It strongly influences the group's willingness to interact, question and modify the diagram. It is critical that the finishedness perception is aligned with the modifiability possibilities.

Quotes: *"Drawing on the whiteboard is temporary and so people will take more risks. It is better for prototyping and exploration, then when you are comfortable you take a photograph or you make a final draft on a flip chart".*

3.1.4 Directed focus

Definition: extent to which the diagram draws attention to one or more items.

Similar dimensions in literature: Focus in Eppler [6]: "Draws attention on the issue". Salience in Hundhausen [12]: "Whatever an end user focuses on during the process of construction a visualization tends to become the focus of subsequent discussions mediated by the visualization".

Focus can be usefully dispersed when seeking divergent thinking or different alternative needs to be considered (unevenness by Blackwell [1]). For example using a distinctive color and a bold font on one item placed in the center of the paper, naturally converts the attention to that item as the central point of the discussion; placing various items of the same size and color at the same distance disperses the focus.

Quote: *"It's a problem when you get more engaged with the visual model instead of the idea".*

3.1.5 Inference support

Definition: extent to which new insights are generated as a result of the constrains of the visualization form.

Similar dimensions in literature: free rides in Shimojima [15]: "particular way in which a structural constraint governing representations matches with a constraint governing the targets of representation". Free ride in Blackwell [1]: "New information is generated as a result of following the notational rules".

Inference support is the core differentiator and added value of visualization over text: it allows to gain new understanding "for free" just by changing the visualization type, the focus, or the representational constrains.

Quote: *"It is important to find new insights, to go in search of the mapping which is illumination or explaining".*

3.1.6 Modifiability

Definition: degree to which the items of the visualization can be dynamically altered in response to the dynamics of the discussion (original definition by Hundhausen).

Similar dimensions in literature: modifiability in Hundhausen [12], viscosity in Green [9]: "Resistance to change". Weakly-strongly structured in Star and Griesemer [17]: "Weakly structured in common use; becomes strongly structured in individualist use".

High modifiability enhances the possibility of interaction, but low modifiability is useful because it allows users to give a second thought before making modifications (Useful awkwardness by Blackwell [1]). For example pen and paper is a much less modifiable medium than desktop publishing software, but paradoxically their perceived finishedness is perceived inversely by the general public.

Quote: *"In a typical scenario one person draws something on the whiteboard, then if another person doesn't agree or has something to point out or to add, he or she is invited to go to the board and modify the diagram: it encourages other people to build together a shared picture".*

3.1.7 Discourse management

Definition: control over the discussion and work flow.

Similar dimensions in literature: controllability in Hundhausen [12]: "Facilitates communication by enabling a presenter to dynamically respond to a group's questions". Discourse management supports keeping the discussion on the right track [3]. It is composed of several aspects such as traceability of participants' contribution, progressive evaluation of the discussion toward the goal(s), referencability of the items in the diagram for facilitating participant's reference to the elements of the visualization (Referencability by Hundhausen) and documentation. For example progressive evaluation can be tracked by a visual metaphor such as an arrow hitting a target or a thermometer. Traceability can be obtained by using different colors for different contributions.

Quote: *"Using whiteboards has the drawback that people worry that it is impermanent. When they are comfortable with a visualization they are upset if you wipe it away. It is always better to take a picture of all the outcomes"*

4. Application

Having described the elements of our framework, we can now apply it to a varied set of visualizations used in organizations, in order to show how the dimensions describe the different properties of candidate visualization artefacts. We have chosen three diagrams from business settings for exemplary applications of the framework. The dimensions' ratings in the following examples are a first attempt to bring to light the large variety of visualization forms used in organizations and their effect on collaborative work. In particular, a rating has been assigned by the authors as explanatory illustration of the ongoing research goal. In future the issue of rating reliability and validation will be addressed by having a significant number of users rating the diagrams.

The dimensions rating is based on a 5 point scale, where 1 corresponds to low and 5 corresponds to high, with the detailed rating scale described in Figure 3.

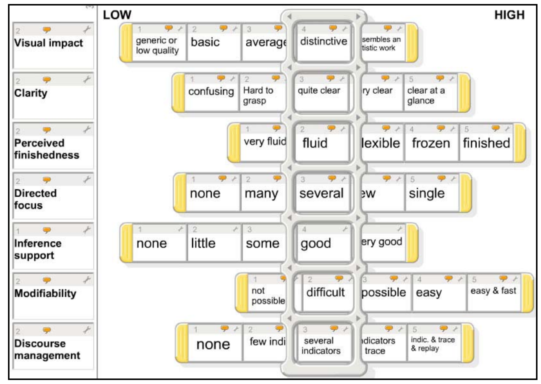

Figure 3. Rating scale

4.1 Visual metaphor

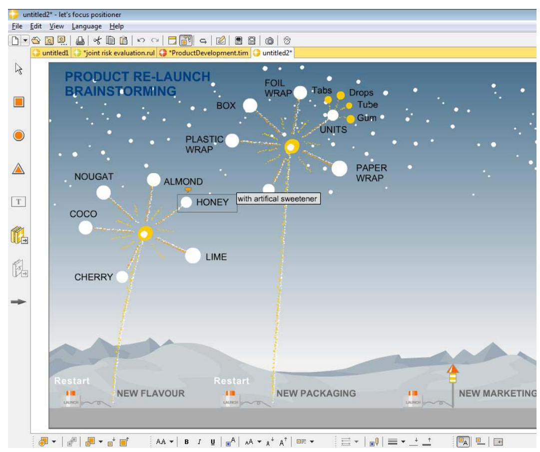

Figure 4. Visual metaphor

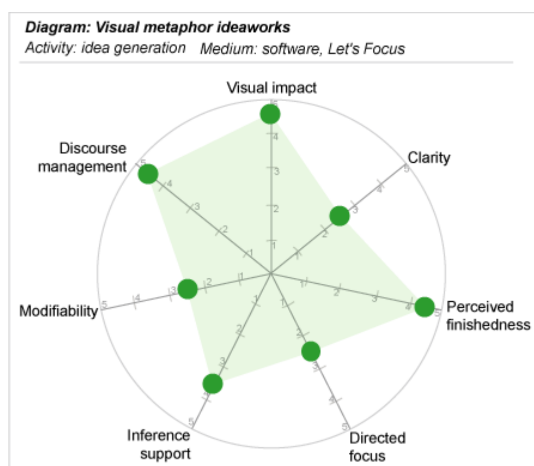

Figure 5. Visual metaphor rating

Figure 4 illustrates the visual metaphor of fireworks, used in the activity of idea generation in group, regarding the re-launch of products. Participants' contributions in the brainstorming discussion are captured as firework bursts.

The *visual impact* of this metaphor-based diagram is very high. However *clarity* and *directed focus* are affected negatively, because the eye-catching graphic is slightly distracting. The *modifiability* is high, as well as *discourse management*, because the diagram is produced with a specific collaborative supportive software (let's focus). Conversely, it scores high on *perceived finishedness* because the diagram resembles a final piece of work instead of a discussion tool.

4.2 Mind map

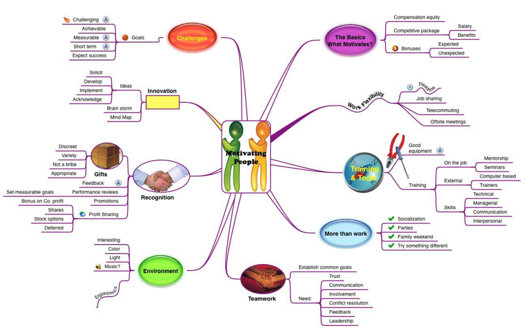

Figure 6. Mind map

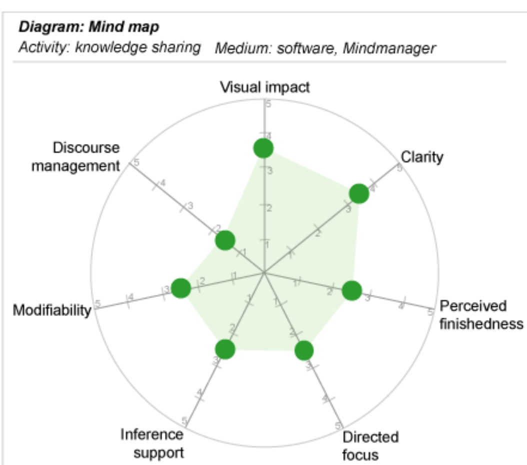

Figure 7. Mind map rating

The mind map in Figure 6 is used for the activity of knowledge sharing, and in this particular example, for eliciting best practices and techniques for motivating people. Participants can contribute with their knowledge, which is externalized and shared by adding their insights to the shared visualization.

The diagram is visually appealing and easily understandable due to the colorful images and the familiarity of the diagrammatic form, therefore *visual impact* and *clarity* score quite high. However the *perceived finishedness* and *modifiability* are rather low, because the visualization is created with a software package (Mindmanager by Mindjet) which is quite viscous and also does not provide good support for *discourse management*.

4.3 System diagram

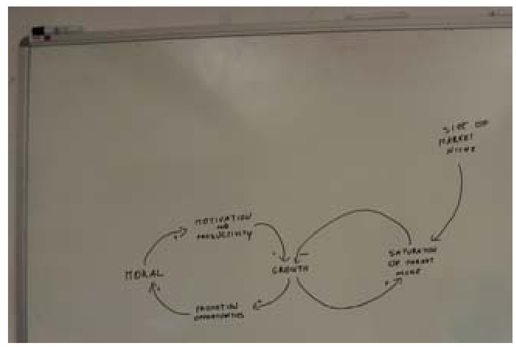

Figure 8. System diagram

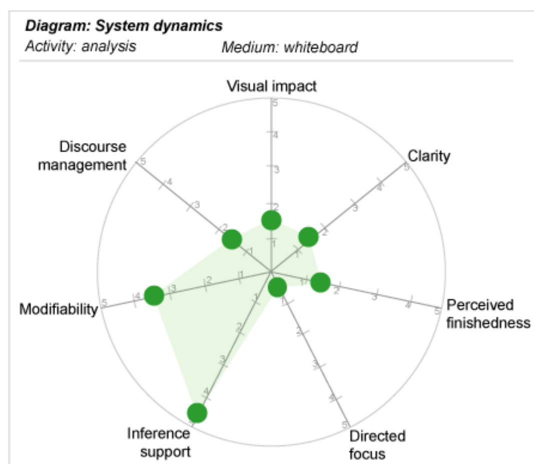

Figure 9. System diagram rating

The system dynamics diagram in Figure 8 is a highly formalized diagram that depicts the positive and negative influences on elements of a system, creating positive and negative loops. The shared understanding and analysis of the system is supported by a few unambiguous rules for creating the representation.

This diagram scores low on *visual impact* and *clarity* as it is not very appealing and also quite hard to understand, because system diagrams are not a broadly familiar to the general public. Directed focus is also very low as there are no items on focus. However the medium on which it is drawn, the whiteboard, is highly *modifiable*, and the diagram form provides high *inference support* to discover new and non-trivial insights.

5. Activity types and tradeoffs

From the small sample of visualizations examined we can already see that there is a great variety of diagram forms, media and activities, and that this great variety can be compactly described and compared by the proposed framework.

We now consider different collaboration task types that are relevant in organizational collaborative meetings. Then we examine what the dimensions tradeoffs are, and how they relate to the activities.

5.1 Activity types

Among the many collaborative tasks relevant for organizational processes, we focus on six activities that often pose challenges in terms of the effective and efficient integration of dispersed knowledge: idea generation, general knowledge sharing, problem analysis, option evaluation, deliberation (decision elaboration) and planning. In future development of our research we will try to match those activities with specific characteristics of visualizations, by using the framework presented above. From the analyzed diagrams in Section 4 we can see emerging patterns of connections between dimensions rating and suitability for a specific activity type or task.

Visual impact is more relevant for providing inspiration when creatively divergent thinking is needed, such as for idea generation and knowledge sharing. In the visual metaphor example (Figure 4) the high visual appeal of the picture and the fireworks metaphor provide strong support for creative thinking.

Clarity is crucial in convergent thinking activities, such as option evaluations (assessments) and deliberation. Conversely, during concentrated creative phases such as idea generation, clarity may be low.

Low *perceived finishedness* is valuable for idea generation, knowledge sharing and analysis because giving the visualization an incomplete look (for example by avoiding overly perfect colors, shapes or surfaces) causes people to assume the visualization is under revision and this stimulates them to contribute. For instance in the System dynamic diagram (Figure 8) the visualization is highly provisional, as it is drawn on a whiteboard, and therefore it makes people more comfortable with questioning the model and offering contributions.

Directed focus is particularly relevant during evaluation and deliberation in order to minimize misunderstandings. *Clarity* is always positive but it is crucial during the information-intensive phases of problem analysis, evaluation and deliberation.

Inference support is a highly valuable added value for analysis, evaluation, and deliberation. For example system diagrams (Figure 8) combine the big picture of complex phenomena with the mutual relationship and influences of the single components.

Modifiability is positive in general, but not always crucial for evaluation and deliberation. In fact low modifiability can be positive for focused decision making activities. By contrast, modifiability needs to be very high when the diagram supports tasks that are undergoing continuous revision.

Discourse management support is always positive, although not always necessary. Software-based interactions in general have more supporting tools for control over the work flow: for example the modifications to a diagram can be traced back and replayed and easily stored (for documentation).

5.2 Tradeoffs

The phenomenon of tradeoffs between dimensions was first introduced in Green and Petre [10]:

"fixing a problem with one dimension will usually entail a change in some other dimension"

For a better understanding of the dynamics between the collaborative dimensions of the proposed framework, we tried to identify and describe the tradeoffs. However we do not claim that those tradeoffs are by any means definitive, as further research and testing are required. Our intention here is only to provide an explication and example of the mechanism of tradeoffs. In Figure 10 we present an example of application to the first diagram we considered in the previous section, the visual metaphor (Figure 4 and Figure 5).

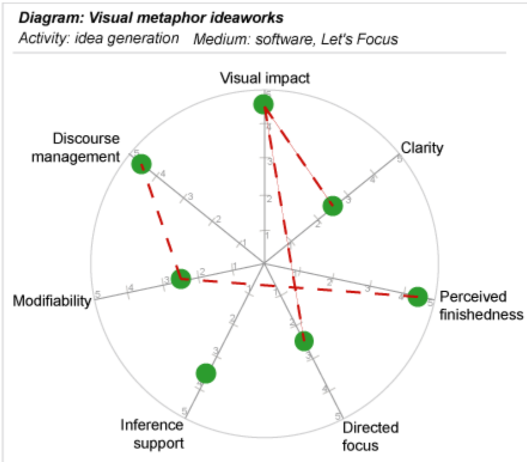

Figure 10. Tradeoffs

The logic behind these tradeoffs can be described as follows.

Visual impact and clarity: high visual impact has a negative effect on the clarity of the representation, in fact, a visualization that resembles an artistic work is less effective in terms of providing easy to comprehend concepts.

Visual impact and directed focus: when the visual characteristics of a diagram are appealing, the focus and attention increase, but only to a certain extent. When the visual stimuli are very high, then the focus will diminish because the attention is caught more by the aesthetics than the content (defined as Salience by Hundhausen [12]).

Perceived finishedness and modifiability: if a visualization is perceived as a final polished product it has a negative effect on the participants' willingness to contribute, criticize and therefore modify the visualization.

Modifiability and discourse management: The extent to which a diagram can be easily changed has an influence on the work flow in the group: when modifiability is high, the group coordination is more difficult.

Having analyzed the constraints between the dimensions we will now examine the constraints imposed by the medium in which the visualization is represented.

5.3 The role of the medium

As expressed by one of the interviewed consultant:
"*Different media produce different behaviours in people".*

We can observe that the dimensions are affected also by the support offered by the medium. The choice of alternative media such as a whiteboard, paper or computer-based interaction, strongly affects people's willingness to make contributions and collaborate. Even within the same medium, for example paper, if a pencil or a felt-tip pen is used it changes the modifiability possibilities. Therefore if the medium is very viscous, modifiability is affected negatively because people will be more afraid to contribute. It also strongly affects perceived finishedness: a diagram on a sheet of paper is perceived as more provisional than a computer-based projected presentation, although modifications can often be made more easily in a software based application (cut, paste, move). Some software specifically designed for collaboration can have high *discourse management* support (traceability, history, replay) that can never be achieved using paper.

6. Outlook and conclusions

The contribution of this paper is to introduce a framework for the systematic description of visualization properties, to be used in the design of collaborative knowledge work.

We started by reviewing existing literature, and conducting interviews to gain practitioners' perspective on prior research findings. We have proposed the development of a new framework based on cognitive, communicative and collaborative dimensions. We provided an exemplary application of the framework to three interactive graphic formats for a varied number of activities, underling the tradeoffs among different dimensions and the relevance of the medium. Through these examples we have shown the great variety of diagrams commonly used in organizations and how we can analytically describe their characteristics.

Our future research will aim at refining and consolidating the framework, by testing the reliability of the framework for rating and improving the dimension descriptions, through think-aloud tests and visualization ratings.

Secondly, we want to match the collaborative dimensions ratings with activity types, as our final goal is to provide a tool for facilitators to easily choose, modify or create the appropriate visualizations for any collaborative situation. To achieve such results we believe that different methodologies could be considered, as for example knowledge activities rating or card sorting techniques. In addition to these techniques, classic research methods can be considered, such as field observation, case study analysis (Yin [17]) or experiments (Keppel and Wickens [12] and Hollan, Hutchins and Kirsh [11]). Researching the dimensions of collaborative visualizations thus requires, in our view, the careful and triangulated combination of context-rich field studies and accurate experimental methods.

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