

## TOWARDS A SCIENCE OF ENGINEERING DESIGN TEAMS

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### 1 BACKGROUND AND OBJECTIVES

The last few years have witnessed a renewed interest in various typologies to classify the dominant or preferred behaviors (cognitive and social) of engineering designers during the product development process. See for example research on p-designers (high experience and little or no training in formal design methodology) and m-designers (low experience with training in formal design methodology) conducted by Gunther et al [1]; research on the relationship of individual styles of problem solving to representations in the design process by Eisentraut et al [2]; research on the relationship between the diversity in the personality of team members and design performance by Wilde [3]; study of how individual particulars such as theoretical education and demand for quality affect the outcomes of critical situations in industry by Frankenberger et al [4]; behavioral and electrophysiological study of effect of experience (novice vs. expert) on design problem solving by Goker [5]. Coincidentally, this renewed interest comes at a time when new technologies, which increase our capacity to observe designers in action, have become widely available. Among the new technologies that have come into recent use by researchers are the video camera, the functional magnetic resonance image scanner, and the computer. Furthermore our ability to process the observed data has also improved, such that we can better determine the relevance and predictive accuracy of these typologies. These improvements in the instrumentability of design teams suggests that in future we will be able to build better models of the workings of design teams and formulate hypothesis which can be readily tested and validated. This paper is conjectural and represents an attempt to plan future research by building on past empirical work in the context of modern tools.

Today we compose teams primarily based on the background experience in a given field of knowledge and the task requirement. For example we may compose a team consisting of two electronics engineers and one mechanical engineer. This kind of composition, based on domain knowledge, in addition to other structural factors like the organizational arrangement, communication tools, and computer tools is analogous to the "physics" of teams. On the other hand a composition that considers the cognitive style of the individual members, their temperament, their response to stressful situations, and the pattern of interaction with other team members is analogous to one based on the "chemistry" of teams. The objective of this paper is to explore a future scenario in which such a science can be applied to real world situations. A priori this exploration will be based on three key ideas. First is to select a commonly observable design phenomenon. We believe this will keep us grounded in design practice and help in prioritizing our research questions. Second is to build on the "observe-analyze-intervene" research methodology [6]. This methodology is a form of action research that emphasizes intervention as an important way of understanding complex systems. The

third idea is to use computer simulations as an integrating tool in our work. We intend to draw on the results of empirical studies we have done and other related studies in coming up with testable hypothesis. Based on our previous work [7,8] we were struck by the high number of concepts and variables that need to be considered by researchers when studying design teams. Computers give us the ability to externalize our evolving understanding of design teams into symbolic models, which can then be easily shared and manipulated. We believe this approach will make it much easier to consolidate our findings and develop our understanding. In the rest of the paper we elaborate on each of these ideas using concrete examples. We will then conclude by reflecting how such a science of design teams as we propose could be applied to future design scenarios.

## 2 Classic design problem: "Requirements Deviation"

Our first idea is to choose a commonly observable design phenomenon. We believe this strategy will appeal to practicing engineers and thus make it easier for us to find subjects within this population. Furthermore we believe that grounding our theories in practice will give us an important criteria for prioritizing our research questions. Figure 1 illustrates a common problem we believe most designers are familiar with. This is a problem in which over the course of time the request of the client becomes transformed into an artifact that fails to meet the client's needs.

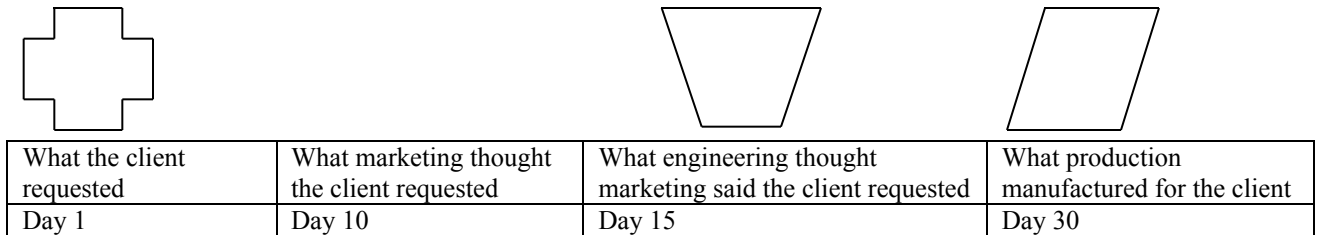


Figure 1. An illustration of the requirements deviation problem

We believe a science of design teams will enable us to estimate the likelihood of this deviation or "creep" from the original intent. In other words we would like to make predictions of the form described below:

When a design team D with properties D1, D2, ...  
working in an environment E with properties E1, E2, ...  
in a market M with properties M1, M2, ...

is assigned a design problem P with properties P1, P2, ...  
in time T with properties T1, T2, ...

the result will be Q with properties Q1, Q2 ...

As seen above, there is a high number of variables necessary to make any good predictions about the performance of design teams. We believe our research approach using a combination of multiple observation methods and simulation-based analysis is the necessary and sufficient situation to address such a complex issue. We will elaborate on the specific elements of this approach in the next two sections.

### 3 Research Methodology

The "observe-analyze-intervene" method is an iterative approach to research that emphasizes the development of interventions as a way to perturb a system and test underlying assumptions. Illustrated in figure 2, the method begins with the observation phase whereby a real world phenomenon is observed and recorded. In the next phase, the data collected is analyzed and interpreted. This interpretation is then used in the third phase to inform the design of new tools and methods that will impact the behavior observed in the initial real world situation.

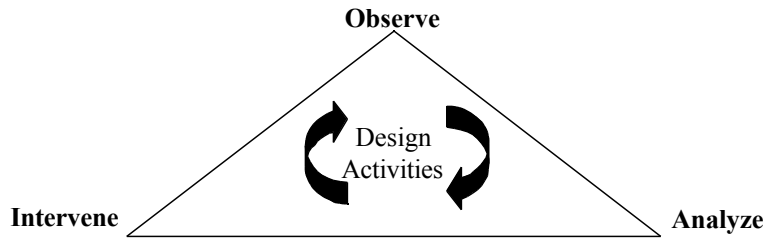


Figure 2. The Observe-Analyze-Intervene methodology, through its intervention step allows a complex system to be perturbed and reveal hidden assumptions.

The cycle is then repeated in such a way as to deepen one's understanding of the real world phenomenon and, refine or change the tools and methods that were earlier introduced. The method has been very useful to us in the design of computer and communication tools to support design work and we believe it offers a practical way to develop a science of design teams.

As we discussed and thought about the new technologies mentioned earlier (video camera, functional magnetic resonance scanner, and computer simulation) we realized that essentially all three, in addition to the more traditional social science tools of interviews and surveys, allowed us to access the design process from different perspectives and each had its limitations. For example video/audio recordings were useful for observing external actions and audible utterances, but were of limited use when it came to knowing anything about the nature of the designer's thought process. Brain imaging would allow observation of the internal cognitive activity of the designer but tell us nothing about the designer's beliefs, motivations, and attitude. Interviews and questionnaires will allow us to learn more about a designer's beliefs, motivations, and attitude, but nothing about what the designer actually does in practice. We shall now describe each of the three primary observation methods in turn using illustrative examples from empirical work.

#### 3.1 Video Observations

Effective communication between engineering design team members is essential for high performance in product development. In turn effective communication depends on successful transfer (sending, receiving and processing) of information. This information may range from data and facts to creative ideas. Previous work by Felder and Silverman has shown that individuals differ from one another in how they prefer to receive and process information [9]. They referred to these preferences as learning styles, and developed a set of five dimensions, each consisting of a pair of poles (shown in parenthesis), that could be used to describe individual preferences. We believe these dimensions namely Perception (sensing, intuition); Information Reception (visual, verbal); Information Processing (active, reflective); Information Organizing (sequential, global); and Information Organizing (inductive, deductive).

deductive) will be of particular importance to understanding communication difficulties in design teams. Figure 3a shows a sample profile for an individual in the information reception dimension.

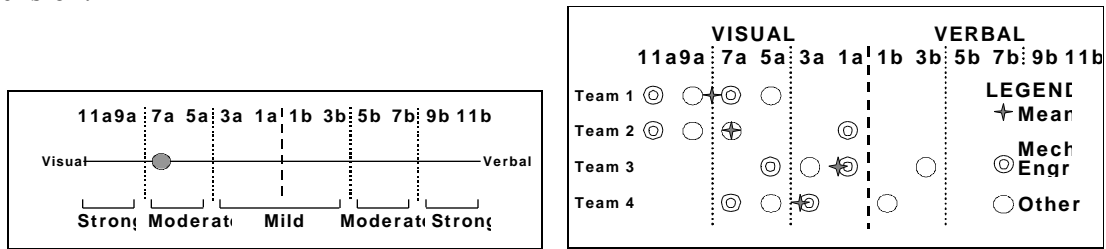


Figure 3. a) A sample profile of an individual with a moderate preference to receive information visually. b) Team learning style distributions. Team 1 was formed such that its members, on the average, strongly preferred to receive information visually. Team 2 had a moderate preference to learn visually. Both Team 3 and Team 4 had a mild preference to receive information visually.

In a recent study we looked at the relationship between individuals' preference for receiving information and their methods of sending information. It was initially anticipated that each individual's mode of presenting information would match his or her preferred mode of receiving information, and that this match would result in improved communication. To study the congruency (or incongruency) of how individuals prefer to receive information and how they go about sending information an experiment was designed and conducted. The experiment consisted of four teams of engineering educators engaged in a design exercise which was videotaped. Their information reception preferences are shown in Figure 3b.

Results based on analysis of the video tapes and individual Learning Styles Inventories showed that most participants preferred to receive information visually and engaged in drawing very little during the design exercise. If the definition of "visual communication" was expanded to include using drawings, communicative gesturing (i.e., using hand gestures to describe a physical object or action), using hardware, and referencing hardware, visual communication went from comprising an average of 3.8% of the design time to an average of 21.1% of the design time. This means that a large majority of the communication was mismatched with the preferences of the receivers [8].

## 3.2 Interviews and Questionnaires

Since there is only so much we can learn from externally observable events, the use of interviews and questionnaires to complement our video-based observation is imperative. From the types of data that could be gathered through these methods we can learn more about individual attitudes and beliefs. Not only will this be important in explaining behaviors we observe, it could also lead to new ways for understanding design.

## 3.3 Brain Imaging

There are several techniques to image the brain, and two of the primary constraints have been the degree of resolution (2D versus 3D) and the invasiveness of the technique. Goker, M. at Darmstadt University for example conducted an electroencephalography study to compare brain activity of novice and expert designers while they were solving simple design problems, Goker [5]. A major breakthrough came with the development of the functional magnetic resonance imaging (fMRI) technique, which is non-invasive and has high 3D resolution. FMRI is based on two key ideas: 1) during brain activation the oxygen content of venous blood increases in the region of activation; 2) when a human is placed within a magnetic

resonance field, the increased blood flow causes an increase in magnetic resonance signal intensity.

The resulting techniques of brain imaging essentially allow us to explore structure-function relationships in the brain i.e. how activities in distinct neural processing come together to perform complex tasks such as reasoning, reading, remembering, and visualizing. In recent years, a number of physiological studies, which have shown strong implications for design performance, have been reported in the literature. In a more recent study at the Stanford Cognitive Neuroscience Laboratory, the researchers were able to identify specific brain activities that differentiated between visual experiences, or images, that were later remembered well, remembered less well, or forgotten (Brewer et al. [10]). As an illustration, this latter finding can be adapted to the requirements creep problem by assuming the subjects are representatives of the marketing department. Consider therefore the situation in which we recorded the brain activity of the subjects during the design exercise, where they are generating and refining a space of images that describe a potential solution to the design problem, and a week later, we have them describe this space of images to another set of participants representing the engineering department. Brewster et al's work should potentially enable us to know the strength of the memory of the images for each marketing representative. Conceptually then, this will enable us to predict which representatives will have a higher probability of relaying incorrect information.

## 4 Computer Simulation

We see from the foregoing that the number of variables that would be required in a science of design teams could be very large. We would definitely make simplifying assumptions but even when we do this, we still need to keep track of the variables we eliminate, and the rationale for each assumption. In earlier work, we used a computer simulation program named virtual design team (VDT) to model and simulate the project performance of an engineering organization [11]. While VDT was not specifically written to study small size design teams, we believe it can be conceptually adapted for this purpose. In order to understand our adaptation we will review a few of the basics of VDT.

### 4.1 The virtual design team (VDT)

In general, the conceptual model in VDT seeks to explain how actor variables, task variables and organizational variables affect the duration and quality of an engineering project. Actor variables include elements such as the skill of the actor with respect to a particular task, her preferences for using certain communication devices during task execution and her position within the organizational hierarchy. Task variables include a description of the level of complexity of a task and the degree of uncertainty associated with the task activity. Organizational variables include such variables as the structure and communication policy.

The relationship among these variables is based on a combination of Galbraith's theory of information processing in firms [12] and heuristics for estimating the duration of tasks and quality of decision making during the execution of a project. These heuristics focus on the process by which the first line actor handles exceptions. In general, there are three options: doing nothing (default delegation), reporting to a colleague (lateral communication) or reporting to a supervisor (vertical communication). In communicating with the colleague or supervisor, a further choice is made with respect to the communication medium to use, memo, fax, telephone, e-mail, or face-to-face meeting. These choices are constrained by certain

factors and have consequences. They are constrained by the organizational structure and the communication policy within the organization. The consequences relate to how the choices affect other members of the organization and ultimately the total time to execute a given task.

In a short form, the total time to complete a task  $T$  is the sum of:

- 1) The nominal time (time it will take an average actor uninterrupted)
- 2) The communication time (when an exception occurs this is the time interval between sending a message to one's supervisor or colleague and getting a reply)
- 3) The rework time (if there is a problem, this is the time it takes to fix it).

In addition VDT predicts the project quality based on the number of unanswered communications and number of uncompleted rework. When these numbers are high, quality of work is judged to be poor. For our purposes, we define a product development process as a series of team meetings inter-spaced with individual work and in the next section we will describe a hypothetical situation in which we combine our three observation methods to estimate the likelihood of the deviation in the requirements creep problem.

## 4.2 Image Communication Model

Consider the different possible variables in a simple communicative transaction in which a person A wants to communicate an image to a person B. The send mode could be words, gestures, or sketches; the receiver may be inattentive, half attentive, or fully attentive; the image invoked in the receiver's mind could be the same as the senders, very different, or the receiver may draw a blank; the receiver may decide to verify correct reception or not, etcetera. We have illustrated this in the model shown in Figure 4. Assuming that each of the variables has an attribute of quality, we can proceed to explore how quality can be measured in each case. Transmission, verification, and confirmation quality could be determined by comparing the input image with the output image. Alignment is found by comparing the mode in which the information is sent by person A with the preferences for reception of person B. For example, reception preferences lie along the continuum from visual to verbal. Send modes are speech, sketches, communicative gestures, using hardware as a simile, referencing sketches, and metaphoric speech or some combination of two or more of these modes which can be classified along a continuum from visual to verbal.

Based on this model we expect to be able to estimate the accuracy of the image being communicated using a factor that is the product of the qualities of transmission, attention, reception, alignment, verification, and confirmation. Using the same model we can also estimate the time it takes to communicate an image as the modified sum of the transmission the reception time, the verification time and the confirmation time. We expect individuals will differ in terms of their likelihood not only to expend time in these areas but also to iterate through the process until confirmation is achieved. Armed with these estimates we can for example estimate the number of meetings it would take for a given team to successfully communicate a given set of images. We can similarly estimate the failure rate we can expect given their likely behaviors as observed from their interview and questionnaire data, brain scan recording and video recording, thus predicting the likelihood of the team to deviate from the client requirements. Figure 5 shows how computer simulation can be used in the analysis phase of our work and in so doing complement our observation methods and lead to more informed interventions.

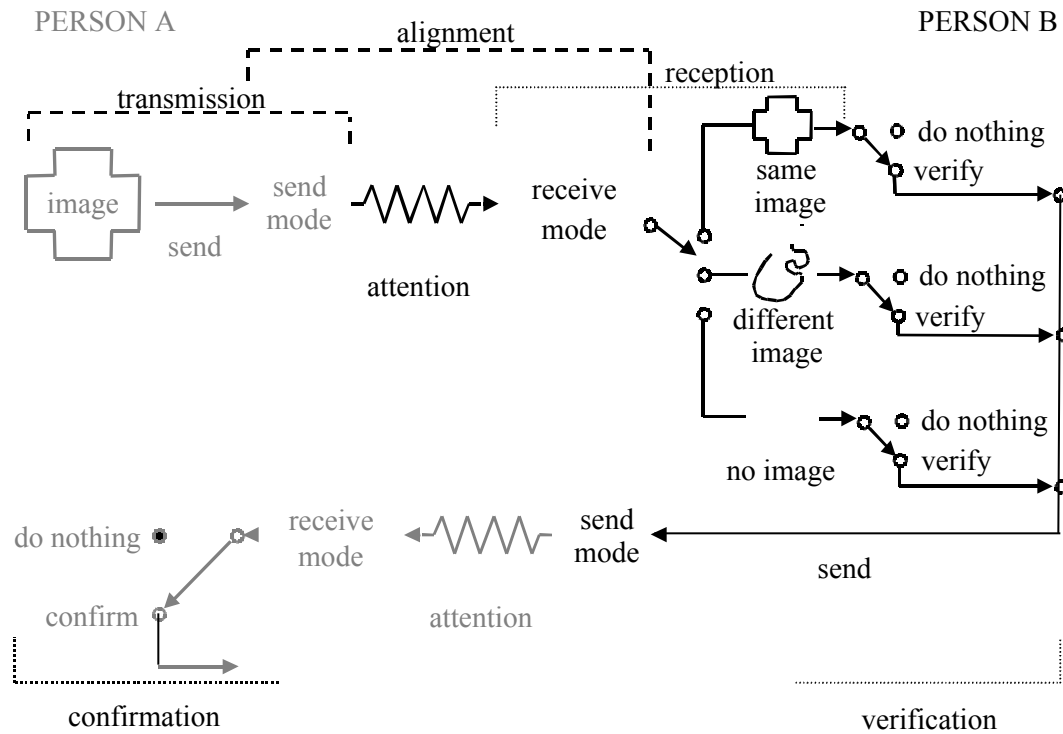


Figure 4. Model of a simple communicative transaction in which person A attempts to communicate an image to person B. The basic steps are: transmission-alignment-reception-verification-confirmation.

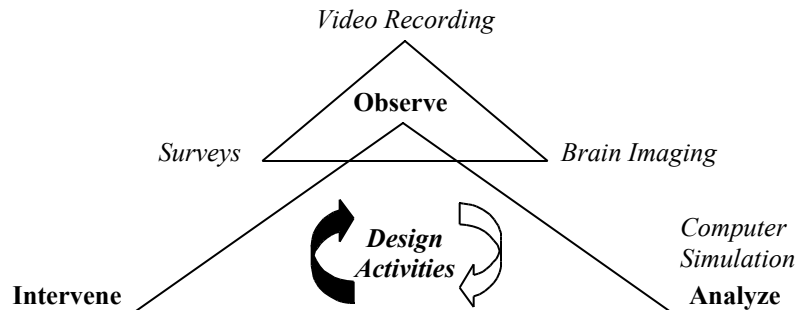


Figure 5. Video observation, brain imaging, and surveys provide three perspectives for observing the design activities. Computer simulation provides a way to analyze the data, develop a better understanding of the interactions, and make more informed decisions about interventions.

## 5 Summary

As we mentioned in the beginning, our aim was to make a sketch of future research by building on past empirical work in the context of modern tools. In so doing we have described a scenario whereby the improvements and availability of better tools to observe the workings of design teams will lead to an increase in the accuracy and reliability of our models of design and hence our predictions of design performance. Working from first principles, such a science of design teams will not only enable us to develop new strategies for managing design teams it will also make it possible to develop better environments to support the process. In this future, it appears to us that the quality of the outcome will be judged by both process and product variables - that is both the quality of the final product and the design team's subjective experience of the process, including the quality of their communication.

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