"SOCIOTECHNICAL SYSTEMS (STS) COORDINATION OF VIRTUAL INNOVATION WORK"

Authors:

Bert Painter - BertPainter@moderntimesworkplace.com; Royal Roads University

Pamela A. Posey, D.B.A. - pam@eyesonperformance.com; Sociotechnical Systems Roundtable

Douglas R. Austrom, Ph.D. - daustrom@tpaconsulting.com; Indiana University

Ramkrishnan V. Tenkasi, Ph.D. - rtenkasi@ben.edu; Benedictine University

Betty Barrett, Ph.D. - bbarrett@mit.edu; Sociotechnical Systems Roundtable

Betsy Merck - betsy@merckconsulting.com; Sociotechnical Systems Roundtable

Abstract

This paper reports on a comparative case study of 3 ongoing research and development (R&D) projects, each conducted virtually across multiple worksites, involving varying degrees of task uncertainty at differing stages on an innovation continuum, from basic fundamental research to scale-up and commercial development. This NSF-funded study applied Pava's methodology of sociotechnical systems (STS) analysis to assess the influence of virtuality and task uncertainty on the quality of deliberations. Building on the theory of organizations as information processing systems, different types of technical and social coordination mechanisms were then studied for their impact in reducing or eliminating knowledge development barriers at differing levels of task uncertainty. Technical elements, many based in information systems (IS), appeared to be most significant for coordination where task uncertainty and ambiguity were low. On the other hand, in the context of high task uncertainty, the most significant mechanisms were closely tied to the formal and informal social systems of virtual organizations. Using these findings, a trial application of a 4-step 'STS' methodology for design and use of IS and other coordination mechanisms has now been successfully completed in support of virtual knowledge work at a prominent North American research laboratory. In summary, these findings put into perspective the value of cross-organizational information systems, as a valuable part of the solution of "virtuality" in innovation, but only within a larger sociotechnical systems framework that is the basis for a robust 'STS' collaboration platform.

1 Introduction

Cross-industry, cross-discipline, network-based organization has become central to the emerging practice of science and engineering [1,2]. Hence, countries like the UK have created an 'eScience Programme' to support distributed global collaborations, and in the USA, the National Science Foundation has funded research to improve design of work systems for innovation and knowledge work that is interdependent yet not co-located.

In global software development, coordination has been described as "the major challenge" [3]. There is a perceived "cost to overcome" with global projects and multi-university research, and a key cost driver is coordination [4,5].

It is within this context, that this comparative study of ongoing research and development (R&D) conducted in virtual, geographically dispersed organizations aims to shed new light on the coordination of knowledge work and innovation across time and space. The organizations and projects studied here represent different stages in an innovation process continuum ranging from basic research to scale-up and commercial development. Using sociotechnical systems (STS) analysis as a methodological approach, the research has focused on understanding the influence of virtuality on deliberations and knowledge development at various stages of the innovation continuum. Then, the research question has been about how coordination enables actual achievement of innovation in such distributed, multi-organizational collaborations.

2 Research Sites and Methodological Approach

Three ongoing virtual R&D projects have been included in this study; each project is in a different industry and each deals with different challenges based on the type of virtual work being done. R&D has been characterized as an intrinsic learning system [6] with multiple stages. Each stage is defined by the degree to which participants do or do not know the "what" (objective) or the "how" (method or means) of their knowledge development and synthesizing activities. These stages form an innovation continuum[1] that ranges from high uncertainty tasks in which participants don't know 'what' is the objective in concrete terms and don't know 'how' to operationalize it – to projects with low uncertainty in which participants know 'what' they need to achieve and also know 'how' to achieve it operationally (see Figure 1).

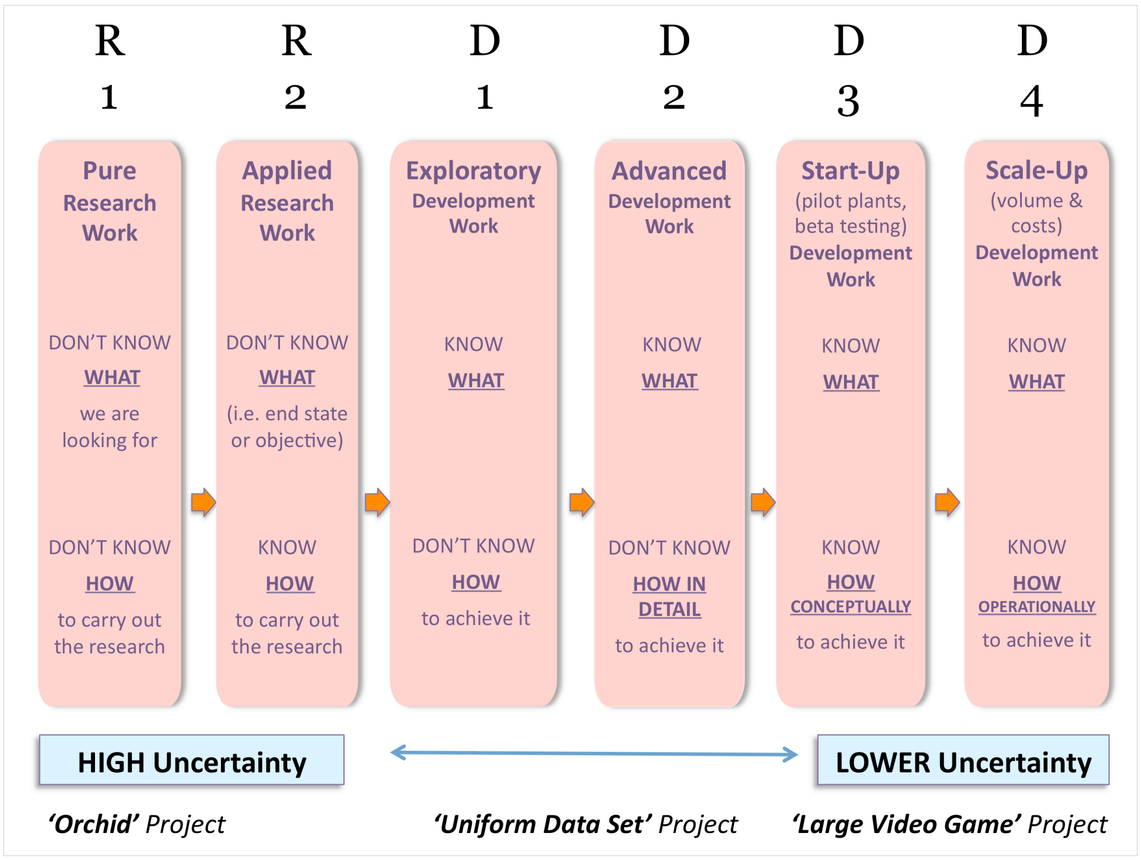

Figure 1: Six-Stage Continuum of the Innovation Process with Location of Case Study Projects

Each project in this study is located at a different stage on the continuum of the innovation process, and each displays a different level of uncertainty in the project work. The "Orchid Project" was a pure research project (R1) on the innovation continuum; The "Uniform Data Set Project" was initially studied in the early development stage (D1), and more substantially at the

[1] Carolyn Ordowich (personal communication, March 26, 2009) outlined an Innovation Continuum adapted from a research portfolio model originally developed and deployed at Bell Laboratories (Revkin, 2008).

advanced development stage (D2) on the continuum; and the "Large Video Game (LVG) Project" was primarily positioned in the scale-up stage (D4), although the systems engineering aspects of this project more closely aligned with the start-up stage (D3) of development.

In addition to being clearly identified as R&D projects, each of the projects has been conducted in its own virtual organizational setting. In each case, the work is comprised of interdependent knowledge-based tasks conducted by participants who are dispersed across space and time and are unable to collaborate face-to-face all or most of the time. Thus, each case exemplifies the primary characteristics identified in prior studies of "virtuality" in work processes [8,9,10,11].

2.1 The Research Sites

The "Orchid" Project represents the field of fundamental, basic research and appears at position R1 on the innovation continuum; it is a collaborative project among theoretical and experimental physicists from research universities around the world. The project, funded by the US Defense Advanced Research Projects Agency (DARPA), is led by scientists from Caltech and includes physicists from universities in the U.S., Austria, and Germany. It is a pure research study in which the researchers *don't know what* they are going to find and therefore, *don't know how* to design a research project that will actually be effective. The degree of virtuality is quite high in the patterns of interaction between faculty and students or post-doc staff.

The "Uniform Data Set" Project (UDS) is a joint project of the National Institute of Health and 29 Alzheimer's Disease Centers across the United States. At the outset, in the development of the "minimal data set" the project was positioned at D1 on the innovation continuum – the parties knew *what* their goal was but *didn't know how* to accomplish it. Based on this experience, this has evolved to a mature development project (D2) that is expanding its investigation based on earlier accomplishments. The chief participants have worked together for a number of years under overall guidance of the National Alzheimer's Coordinating Center. In addition, there are substantial professional ties within and across the centers as the membership consists of a majority of the world's experts in Alzheimer's Disease treatment.

The "Large Video Game" Project (LVG) involved some Start-Up Development (D3) and mostly Scale-Up Development (D4) activities; it incorporates art asset production, website and systems engineering, and testing activities shared among the game developer and vendors around the world. Clarity of purpose and outcome is crucial in the D4 positioning of LVG, and though uncertainty about the 'what' and, to a somewhat lesser extent, the 'how' of the process is low, there is a high degree of virtuality and relatively low face-to-face collaboration in this project.

2.2 Theoretical Background and Methodological Approach

In virtual organizations that involve innovation, work is non-linear and knowledge based. This means much of the work is conducted through discussions and choice-making interactions that are often not face-to-face; these are referred to as deliberations in sociotechnical systems theory. Deliberations are "patterns of exchange and communication…to reduce the equivocality of a problematic issue" [12,13]. They are not discrete decisions—they are a more continuous context for decisions. They have three aspects: topics, forums, and participants. Finally, a deliberation is a unit of analysis (like 'unit operations' in linear processes)—the input, conversion, and output at these 'choice points' is what moves knowledge work forward.

The value of deliberation analysis to identify sources of failure and delays in new product development has been demonstrated [14], [6], [15]. These studies were early applications of

Pava's theory for managing information technologies and non-routine knowledge work processes—a 'second generation' of STS theory based upon the original British-North American tradition of STS developed in the manufacturing and process industry era (Trist & Bamforth, 1951; Emery, 1959; Davis & Taylor, 1972; Cherns, 1976). In his groundbreaking study of office work, Pava (1983) also identified that deliberations often go awry in non-routine knowledge work due to "information gaps".

Building on Pava's work, others have identified the source of such information and knowledge "gaps". In two product development projects co-located within one major consumer products company, Purser et al. (1992) identified four main categories of "*barriers*" obstructing and delaying collaborative knowledge development: (1) *knowledge sharing and planning* barriers, such as lack of cooperation, missing parties, or unrealistic timeframes; (2) *cognitive frame of reference* barriers, associated with differences in language, values, etc.; (3) *knowledge retention and procedural* barriers, such as lack of technical documentation or lack of external consulting; and, (4) *knowledge acquisition* barriers resulting in a lack of available knowledge.

Now, for this comparative case study, concepts of 'deliberations' and knowledge development 'barriers' have been extended to the analysis of knowledge work including *exploratory* development and *fundamental* research where "equivocality" and task uncertainty are greater than in most product development, and potentially more so in the context of virtual organization.

Therefore, to help frame the focal questions of our study, an extensive review was conducted of the literature on virtual organization. Then, scoping interviews were conducted in each organization to gain understanding of the projects and teams involved in virtual innovation work. Through structured interviews and observation, key deliberations were identified and tracked in each worksite to gather core data about the emergence of barriers and the extent to which they were addressed in each real-world innovation process. Finally, follow-up interviews and documentation verified the project outcomes. Indeed, STS analysis provided a powerful lens through which to view knowledge generation and sharing, eventually yielding insight into both social and technical forms of coordination in these virtual work environments.

2.3. Coordination Mechanisms

From an organizational studies' perspective, coordination mechanisms are developed or emerge because of the need for "managing dependencies between activities" of distributed actors [20, 21]. Similarly, from an information systems' perspective, a coordination mechanism consists of "a *coordinative protocol*…(of procedures and conventions stipulating the articulation of interdependent distributed activities)…and on the other hand *an artifact* in which the protocol is objectified" [22].

A connection between coordination mechanisms and the possibility of mitigating knowledge development barriers is based upon theory of organizational information processing [23,24]. This theory postulates that structural mechanisms for coordination must provide the means to handle the amount and richness of information processing required by the *uncertainty* and *equivocality* of an organization's task and environment. In other words, coordination mechanisms make a major difference in how well deliberations in non-routine work incorporate the right information and knowledge, and the right participants at the right time.

Specific mechanisms to permit coordination have been proposed using an information processing view of organization design. However, more specific to global software projects, and most relevant for our study of R&D, Sabherwal [25] condensed many classifications identified in the information systems literature into a typology of four major coordination mechanisms: (1) standards; (2) plans; (3) formal mutual adjustment; and (4) informal mutual adjustment.

Coordination through “standards” relies upon pre-specification of rules, routines, techniques, and targets. Coordination through “plans” is another approach that is mostly impersonal in nature once implemented. Both of these forms of coordination are often built into the structure of information systems. By contrast, in both forms of “mutual adjustment”, coordination is made possible through interpersonal communication, feedback and interaction. In formal mutual adjustment, coordination is “more structured” in design review meetings, supervisory or liaison roles versus informal mechanisms of impromptu or face-to-face communication.

In addition to defining key modes of coordination, theory and empirical research [21], [23], [26,27] have identified the level of task uncertainty and the degree of task equivocality (or ambiguity) as key determinants of the requirements for specific coordination mechanisms. In broad terms, the proposition has been that “more informal, communications-oriented” mechanisms are more suitable “when uncertainty is greater [for example] during the requirements analysis phase”. On the other hand, “more formal, control-oriented” mechanisms are “most suitable when uncertainty is less [for example] during the design, implementation, and testing phases of a project” [25].

In summary, there is considerable prior literature suggesting that task uncertainty is an important factor influencing coordination mechanisms. The intent of this comparative case study has been to take a ‘grounded theory’ approach to extend these findings to a virtual context, and to encompass the full range of the innovation continuum.

3 Findings

3.1 The LVG Project

The Large Video Game project is a critically time-bound commercial product development process based in the USA with a virtual organization of contractors dispersed across the globe. There is limited economic viability for face-to-face interaction among members of the virtual project teams. Production includes 3D animation art assets, systems engineering, website design, and quality assurance. In addition to LVG home-based staff, the virtual organization includes external art asset vendors as well as engineering and website development vendors.

Key deliberations at LVG often occur at the front end of the production process involving ‘choice points’ such as vendor selection. Examples of other key deliberations are defining and estimating outsourced project work and specifying documentation and production requirements.

During the period of this case study, it appeared that knowledge sharing and development barriers were less prevalent in virtual art production than for virtual organization of software engineering and web systems development where barriers included unclear expectations, unrealistic timeframes, and lack of documentation. Delayed data transfer resulted sometimes from incompatible IT systems and/or security issues. Intellectual property issues could also prevent LVG core operations from sharing vital source code with vendors.

In the relatively routine and mature work processes of virtual art production for LVG, information systems have provided vital support for clear expectations about task deliverables. Agreements on acceptable output are coordinated using screen shots, visual targets, emails, extensive digital documentation, and in some cases, web-based project management software.

For engineering and web/online game development, however, a key factor limiting the clarity of expectations is that LVG staff will most often *not know* the fine details of 'how' the outputs are to be achieved. In-house staff may do preliminary design of new website features but detailed technical design is outsourced to a vendor. However, quick feedback that is possible in-house, standing over each other's computers and making 'live' corrections to any misunderstandings has generally been unavailable with engineering vendors in this virtual organization. Another disruptive but unintended factor was that the otherwise very successful 'agile' development process used by LVG staff caused expectations to change mid-course several times for the work of at least one major website contractor. Both of these factors resulted in delay and cost overruns particularly for the first product version of game development observed in this study.

Fortunately, in the time period between the two product development runs, LVG staff made important changes in their coordination mechanisms. Engineering projects are now "chunked" into phases, and vendors must provide schedules for specific deliverables. And, supplementing all of the regular project management tools and systems, LVG made a structural role change to designate a single "product owner" contact person to resolve issues with each vendor for a specific engineering assignment. New technical arrangements have also helped overcome the intellectual property issues that previously constrained the sharing of game source code--a "cloud-based desktop" solution provides vendors access to source code and the ability to integrate new code, while preserving LVG proprietary control. And, selection of any vendor is now dependent upon verification of IT compatibility and an on-site security check. To close yet another gap in knowledge coordination, quality assurance staff in a remote test center can now videoconference into production meetings and 'scrums' at LVG core operations, and thereby increase their tacit knowledge of game architecture. The overall effect of such changes was that the second product run was completed on-time, on-spec, with few quality issues, and on-budget.

3.2 The UDS Project

The Uniform Data Set (UDS) is a longitudinal database of clinical and neuropathological information gathered from Alzheimer's patients in the United States. From 1984 to 1999, the initial development of this database (D1) was the Minimum Data Set that suffered a missing data rate of 20-30%. By 1999, the sponsor agency, the National Institute of Aging (NIA) recognized a need for a reliable, more robust data set as a resource for Alzheimer's research, and established a National Alzheimer's Coordinating Center (NACC) at the University of Washington-Seattle. The Center's mandate was to support more effective collaboration among 29 Alzheimer's Disease Centers across the United States in development (D2) and utilization of a Uniform Data Set. Since then, the NACC has worked with clinical task forces of Alzheimer's Disease Center directors and clinical core directors to develop and update the standardized content of the UDS.

Key deliberations in this project (conducted via videoconferences, teleconferences, email, and sometimes, in person) have selected the 725 data points to include in the data set, an important issue because it determines what longitudinal information will be available for researchers. Another key deliberation has revolved around how to collect the UDS data: as many as 18 standardized forms developed by clinical task forces are now used to collect patient data on socio-demographics, family history, dementia history, neurological exam findings, functional status, neuropsychological test results, clinical diagnosis, and imaging tests. Data managers at each of the 29 Centers monitor the quality of the local data before submitting it electronically to the NACC each month, creating a reliable, large-scale pool of data for scientists to analyze.

The move to the UDS from the original data set raised a number of issues: initially, many of the Alzheimer's Disease Centers resisted the concept of a "coordinating center" and viewed the requirement to use standardized data collection systems as an imposition on being able to collect data best suited to their particular research interests. This created major barriers to knowledge sharing in the early deliberations about what elements to include in the UDS. Other barriers arose from the different frames of reference associated with researchers' diverse disciplines.

The NACC was a purposefully designed coordination mechanism to address the barriers. It has provided an infrastructure, a neutral "referent organization" [28], guiding stakeholder participation for effective deliberations on the design and ongoing refinement of the UDS. This coordination mechanism is activated by the skill of specific individuals in the NIA and NACC in key "network builder" [29] roles: they have built relationships across organizations and disciplines, often through multi-disciplinary, multi-center, technical steering committees.

Furthermore, on an ongoing basis, the NACC coordinates bi-annual face-to-face meetings of the ADC directors and staff. Although infrequent, these face-to-face meetings are one key part of a dense set of relationships among participants in the ADC network. This collaborative 'spirit' has been further strengthened by the larger shared 'mission' to reduce or solve Alzheimer's disease. Overall, the outcome has been that NACC is now instrumental in Alzheimer's research and the UDS has received acclaim as an exemplar of research collaboration [30].

3.3 The Orchid Project

The Orchid project was an international multi-university collaboration by a team of 20 physicists and graduate students led by faculty at the California Institute of Technology (Caltech) who partnered with scientists at other universities in Europe and North America. The project involved experimental scientists and theoretical physicists, many of them physically dispersed. The distributed collaboration most closely studied by our research involved one Caltech lab that fabricated devices for experiments run both on its own equipment and also on quite different equipment in an Austrian laboratory. There was thus very strong interdependence between these two laboratories. However, until the Orchid project, most staff from these two scientific groups had never collaborated. It had been only their brief meetings at international conferences that brought them together with a vision of achieving a "scientific breakthrough" in a new field of science, opto-mechanics (i.e. use of light to manipulate mechanical devices at nano-scale).

Key deliberations within this project focused on the selection of experiments to run, the design of the actual experimentation, and the interpretation and refinement of the data gathered. Knowledge barriers associated with these deliberations were significant. Varied disciplinary roots of the research groups led them to use different language to describe the same data, and each group had its own unique problem-solving approach. A significant challenge was the wide geographic dispersion combined with the high degree of reciprocal and team interdependence between their laboratory facilities. There was a constant threat of failure to utilize knowledge if the diversity of scientific perspectives could not be accessed and integrated for creative problem solving in the experimental process. Another major barrier to the acquisition of knowledge resulted from some incompatibility in the equipment used by the different laboratories.

For coordination, Orchid project scientists made extensive use of shared databases and annotated document repositories. Whenever experiments picked up intensity, digital communication such as skype conversations, sometimes with screen-sharing, or use of electronic whiteboards, texting and email could occur almost constantly during a long, multi time zone work day.

However, the project's greatest collaboration challenges were overcome quite serendipitously. The need to invent a methodology so that devices created at Caltech could run on different experimental equipment in Europe required a detailed understanding by each party of the other's technical capabilities and limitations. The mechanism in this virtual organization that most helped bridge the different frames of reference was what the scientists came to refer to as the role of an "embedded researcher". A European graduate student came to Caltech for a short visit by chance and was able to see differences in methods and technology between the two experimental groups and facilitated solutions to merge their approaches. Another graduate student, from the theoretical school, was also unexpectedly sent to Caltech—he was able to give real-time suggestions to help interpret data for the experimentalists. This liaison or "straddler" role was an ongoing help to coordinate knowledge exchange between project theorists and experimentalists.

Both of these temporary roles proved to be vital coordination mechanisms for this project that over four years yielded a series of internationally recognized publications [31] and produced a "milestone" demonstration of opto-mechanical capabilities.

4. DISCUSSION AND CONCLUSIONS

All of the virtual R&D projects in this comparative case study encountered substantial knowledge development barriers, and utilized coordination mechanisms to overcome barriers. Of the four main categories of coordination mechanisms (standards, plans, formal mutual adjustment, informal mutual adjustment), all general types were utilized *to some degree* in specific examples developed within each project in our study sample. However, the type of mechanisms that project participants indicated were *most significant* in mitigating knowledge barriers varied noticeably according to the project task (see Figure 2).

Coordination Category	Case Examples	'Orchid'	'UDS'		'LVG'	
		R1	D2	D3-D4	D3	D4
Coordination by **STANDARDS**	•Output Standardization—prototype, screen shots, visual targets					+
	•Skills Standardization/training			+	+	+
	•Standardization of Processes					+
	•Diagnostic instruments			+		
	•Data formats			+		+
	•Error-tracking procedures					+
Coordination by **PLANS**	•Delivery schedules			+	+	
	•Project milestones			+	+	
	•Requirement specifications			+	+	
	•Sign-offs				+	
	•Financial incentives			+		
	•Compelling 'mission'/goal	+	+			
Coordination by **FORMAL MUTUAL ADJUSTMENT**	•Site inspection/verification				+	+
	•Hierarchy/vertical communication				+	
	•Shared database/repository					
	•Formal meetings/status review	+	+		+	
	•Steering committees/task force		+			
	•Referent organization		+			
	•Facilitator/'Network Builder' role	+	+			
	•Liaison/'Straddler' role	+			+	
Coordination by **INFORMAL MUTUAL ADJUSTMENT**	•Impromptu communication	+	+			
	•Informal meetings	+	+			
	•Conferences, workshops	+	+			
	•Site visits	+				
	•Temporary co-location	+				

Key: + Designates Active & Significant Coordination Mechanism in a specific virtual R&D Project

Figure 2: Most Significant Coordination Mechanisms in Sample Virtual R&D Projects

One theme in these findings is an apparent correlation between most impactful types of coordination mechanisms and differing levels of innovation task uncertainty. For those activities and projects with the lower degree of uncertainty, the more impactful mechanisms were technical, impersonal, relying on an a priori specification of action or targets-- for example, the screen shots, visual targets, and project management software that provided 'standards' and 'plans' to coordinate expectations between LVG and its art production vendors. However, the social, or mutual adjustment mechanisms that are more indeterminate and rely on extensive ad hoc human interaction had more impact in mitigating barriers in those activities and projects where there was higher uncertainty about outcomes and process: for example, the "embedded researchers" who contributed vital liaison across disciplines and institutions in the Orchid project, and functioned much like the "straddler" role described as a conduit for "transfer of tacit knowledge" in global software engineering projects [32,33].

In sociotechnical terms, the social or mutual adjustment mechanisms are based *primarily* in the social sub-system of a work organization, while standards and plans are based *primarily* in the technical sub-system (see Figure 3). For example, a project status review meeting (as a formal mutual adjustment mechanism) may rely upon a teleconferencing technology application, but the primary contributions to the review meeting as a coordination mechanism are located in the leadership and other roles, mutual task expectations, and relationships within the virtual team or groups performing the work [34]. On the other hand, a standard such as a format for reporting clinical data in the UDS project is indeed a 'resource for situated action' [35] and does rely upon interpretations made by people gathering data such as neurologists, but the data format is essentially a technical artifact that embodies the general stipulations of a protocol organizing tasks for reporting valid and useful research data.

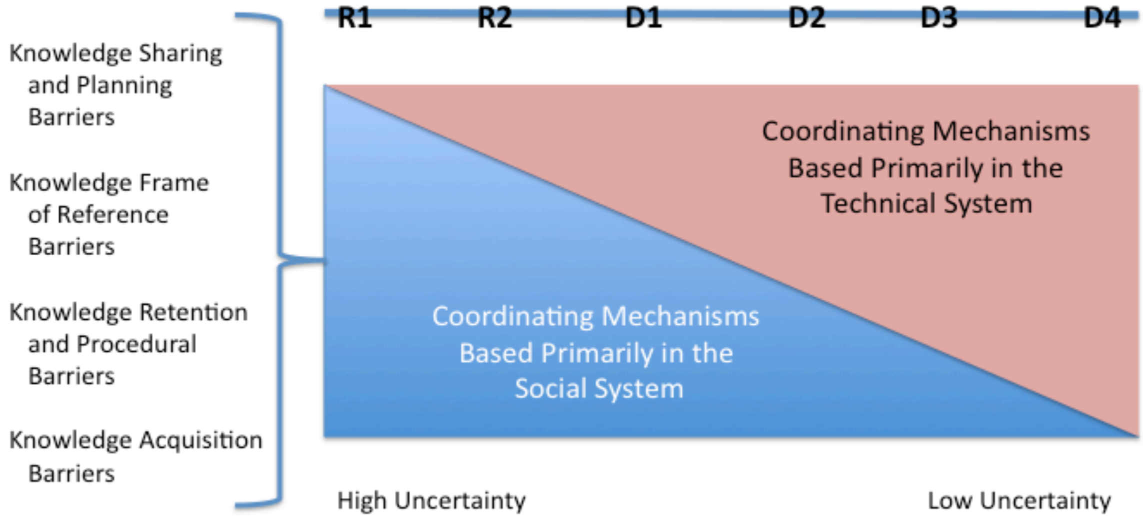

Figure 3: Differing Impact of 'Technical' and 'Socio' Forms of Coordination in Innovation

Indeed, the 'technical' and 'socio' dimensions of coordination appear to complement one another. Neither is entirely sufficient for overall coordination, but each tends to be more impactful, depending upon the stage of innovation or nature of knowledge work.

How different types of coordination mechanisms are complementary is exemplified by the experience in the LVG project for systems engineering and website development. At this (D3) stage of innovation, effective coordination required a combination of important 'technical' elements of web-based project management software and short time frame "chunking" of project plans, along with a formal mutual adjustment mechanism in the form of a new "product owner" role within the social system of relations between LVG and its vendors. Conversely, what made the informal mutual adjustment mechanism of the Orchid project scientists' infrequent face-to-face discussions most effective were detailed plans and data-sharing done prior to their meetings.

Another form of interaction between the 'socio' and 'technical' dimensions of coordination is the significance of how these mechanisms are *used*, quite aside from the process of their design or selection. For example, as suggested by prior studies [36], frequent annotation of documents in web-based repositories made the sharing of information and the interpretation of experimental data much more understandable and productive for the theorists and experimental scientists scattered across the globe in the various Orchid project teams.

Such use of data repositories enabled dispersed scientists to experience a form of collaboration awareness: "an understanding of the activities of others, which provides a context for your own activity" [37]. This functioned like an implicit coordination mechanism providing "task knowledge awareness" [38] about how colleagues' perspectives on particular research data were evolving during the life of the project. Targeted use of this form of 'awareness' has been found to be especially valuable in non-routine work. Also observed in our study was the use of instant messaging technology that provided "presence awareness"--the feeling that physically distant colleagues were available to each other and could provide immediate feedback on important topics [39], thereby supporting informal mutual adjustment that was particularly helpful in coordination across diverse knowledge and organizational boundaries as existed in the Orchid and UDS projects.

The case of the UDS project with its challenges of effective data collection highlights another critical aspect of coordination mechanisms, namely, "malleability" [22]. In this respect, the various clinical task forces involving UDS project stakeholders have played a key role in continuous modifications of data formats and clinical instruments to ensure that these mechanisms meet the needs of diverse users as well as maintaining the vital integrity of the Uniform Data Set for 'downstream' Alzheimer's research.

Taking further this notion of 'fit' between a coordination mechanism and its 'field of work', the case of quality assurance testing in our study of the LVG project provides some indication of the importance to distinguish "different modes (i.e. alpha levels) in which a protocol-based system…can support [coordination]…from the more constraining mode to the less constraining", in terms of whether or nor there is affordance for users to skip or defer any action within the intended process [40]. In one key change between an early and later production run of the LVG project, in order to address knowledge and skill gaps among high turnover student testers employed by the QA contractor, more prescriptive "scripts" were given to testers, which helped greatly to improve the ratio of 'bugs' solved per work hours.

In summary, many of these effects occur in co-located work as well as in virtual organizations. However, participants in this study reported that, compared to their experience of co-located work, barriers to the development of knowledge (e.g. intellectual property issues, divergent priorities) were more difficult to manage in the virtual context of innovation. And, although scientists and their graduate students used virtual workspace IT tools for task coordination [41], such as instant messaging, electronic whiteboards, video conferencing, and network databases, difficulties of communicating tacit knowledge and the data interpretation challenge of "sense-making" [42] were accentuated in these case study projects of fundamental research and advanced development in a virtual context.

Even though there is "a common notion that collaboration technology and bandwidth will allow a virtual team to perform as if co-located…evidence shows this notion to be a naïve myth" [43]. One implication for practitioners from this comparative study is that effective coordination of virtual innovation work can benefit from a sociotechnical systems approach. Modern STS methodology (updated for non-routine work) provides a way to utilize elements of *both* social *and* technical sub-systems to assess and overcome "coordination costs".

As an indication, a recent trial application of these research findings in a major North American research laboratory was viewed very favorably by scientists and staff challenged with coordination of teamwork across time, space, and changing environments in the laboratory and its network of related universities, and private sector stakeholders. The work of these scientific teams covered a wide variety of topics, at differing stages across the innovation continuum.

A series of workshops were held periodically over several months at the laboratory to share the findings of this research study. During and between workshops, scientists and their fellow team members applied the concepts to analyze the process of their teamwork, and then, select or develop and evaluate new coordination mechanisms, using a four-step STS design methodology:

- First, locate the project or specific knowledge work on the Innovation Continuum. Awareness of the positioning of a team's work on the continuum, (and this positioning may well move during the life of a project), helps anticipate the types of 'technical' and/or 'socio' mechanisms that are likely to be most significant in mitigating knowledge development barriers (see Figures 2 and 3).
- Secondly, identify the key deliberations or 'choice points' that are essential to move the team's work forward. Deliberations are defined by a topic (e.g. what experiment to run, what software feature to develop), and they require specific information and knowledge, with the involvement of specific participants with differing perspectives and interests.
- Thirdly, analyze the most significant knowledge development barriers that potentially or actually impede the quality of these key deliberations. To help maintain alertness to such barriers, utilize the typology of (1) knowledge sharing and planning barriers, (2) cognitive frame of reference barriers, (3) knowledge retention and procedural barriers, and (4) knowledge acquisition barriers.
- Fourthly, select, design, and/or utilize appropriately the specific coordination mechanism(s) that seem most capable of mitigating the identified knowledge development barriers. This aspect of "designing" [44] for effective collaboration needs to be understood and practiced as a continual, unfolding process in order to address both the evolution in the type or stage of innovation/knowledge work and the ever-changing context of virtual teamwork.

At the conclusion of the trial application, over 90% of the scientists and staff reported in a feedback survey that these concepts and methodology "will improve how we work together" and "address [distributed teamwork] issues we were trying to solve". The coordination mechanisms developed by the scientific teams included a combination of new standards and procedures, new systems for information sharing and storage, and redesigned team roles.

The findings of the research reported here and the recent application experience put into perspective the value of 'technical' elements of cross-organizational information systems (IS) and web-based collaboration technology. They are a valuable part of the solution for coordination of "virtuality in teams" [8], but only within a larger sociotechnical systems framework that is the basis for robust 'STS' collaboration platforms with both 'socio' and 'technical' components to support effective virtual innovation. Indeed, further development of such an integrated approach could be a new "practical scientific collaboration" [45] across the disciplines and communities of information systems and sociotechnical systems design.

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