Individual Centrality and Performance in Virtual R&D Groups: An Empirical Study

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Communication technologies support virtual R&D groups by enabling immediate and frequent interaction of their geographically-distributed members. Performance of members in such groups has yet to be studied longitudinally. A model proposes not only direct effects of functional role, status, and communication role on individual performance, but also indirect effects through individual centrality. Social network analysis was performed on e-mail samples from two time periods separated by four years. Analysis revealed both direct and indirect effects as hypothesized; however, the indirect effects were more consistent in both time periods. The clearest findings were that centrality mediates the effects of functional role, status, and communication role on individual performance. Interestingly, centrality was a stronger direct predictor of performance than the individual characteristics considered in this study. The study illustrates the usefulness of accounting for network effects for better understanding individual performance in virtual groups.
(*Field Study; Path Analysis; Social Science; Hierarchy of Authority; IS Project Teams; Electronic Mail; Social Network Analysis; Centrality; Roles; Individual Performance*)

1. Introduction

Nearly 15 years ago, research and development (R&D) organizations engaging in innovative tasks began an obvious and swift transformation toward using virtual groups rather than counting on contiguous, face-to-face interaction (Drucker 1988). Today, in the face of widespread use of virtual groups, it is surprising that so little is known about the extent to which this virtualization can affect the performance of group members. This study focuses on such effects by examining individual performance in a virtual group containing members of various corporate and academic research units working together on a large-scale, innovative R&D project.

Virtual groups share certain properties with face-to-face groups. They clearly fit previous definitions of a group: Virtual groups are composed of two or more individuals engaged in a lasting relationship, pursuing a common interest or goal, who influence each other through social interaction, formal and/or informal structures, and a sense of group membership (Forsythe 1983, Baron et al. 1992, Aldefer and Smith 1982).

In contrast, virtual groups differ from face-to-face groups in many respects. The most visible difference is that virtual groups are often geographically distributed, forcing individuals to overcome "space, time, and organizational boundaries (by employing) webs of communication technologies" (Lipnack and Stamps 1997, p. 7). At the extreme, a virtual group is a collection of individual members in separate locations, seldom or never engaging in face-to-face

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contact, and communicating only by using technology. It is also common, however, for virtual groups to have clusters of co-located members (Cramton et al. 2003). In any event, communication among members is often the only visible artifact of the group's existence.

More subtle and interesting points of departure include self-management and greatly diminished formality of structure (Ahuja and Carley 1999). There are also new secondary roles and status for virtual group members. A member in a co-located group typically has well-defined roles and status in the organization which simultaneously carry over to, and are reinforced by, work groups that might form. In virtual groups, however, members often belong to separate organizations or organizational units and assume well-defined roles and status relationships that may be completely independent of roles and status relationships in their "home" organizational unit (Ahuja and Carley 1999). Individuals adopt roles and achieve their virtual group status in a more autonomous manner, determined by the resources they bring to the groups.

Perhaps the ultimate comparison between virtual and co-located groups focuses on performance outcomes, providing important clues to the efficacy of virtual groups. A great deal has been written about performance of traditional groups at both group and individual levels of analysis, but there has been very little research on performance in virtual groups. While studies have begun at the group level of analysis (Ahuja and Carley 1999), at the individual level the study of individual performance in virtual groups is still in its infancy (Staples et al. 1998).

Individual performance is likely to be at least as important in virtual groups as in co-located groups because R&D groups draw heavily on specialized expertise and knowledge of diverse individuals located in diverse places (Alavi 1993, Finholt et al. 1990). Increased specialization of diverse individuals implies greater autonomy and higher importance of individual contributions. Thus, better understanding of individual performance in a virtual group can be critical for meeting the goals of the group.

The goal of this study is to examine determinants of individual performance in virtual groups by formulating a research model and testing it in a virtual R&D group. Our model, presented in the next section, proposes that individuals' performance in virtual groups is at least partly explained by role and network characteristics. Later sections describe the research setting, methodology, analysis, and conclusions.

2. A Model of Individual Performance in Virtual Groups

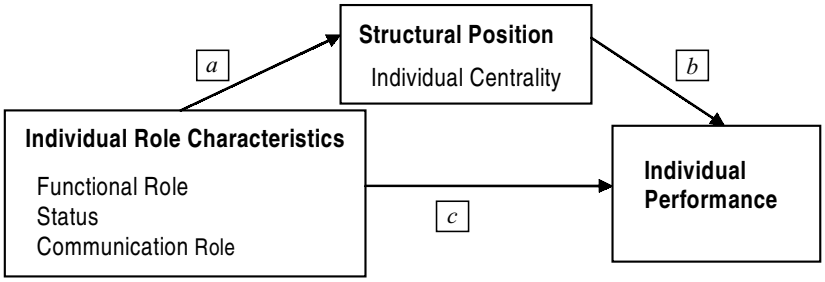
We suggest that in virtual groups, individual role characteristics (functional role, status, and communication role) influence structural position as represented by individual communication patterns within the group (individual centrality), which in turn influence individual performance. Although studies of individual characteristics often include demographic characteristics such as education, skill level, tenure, and experience, we were interested in individual characteristics closely related to network characteristics. Formally stated, the general hypothesis addressed in our model (Figure 1) is that in virtual groups, the relationship between individual role characteristics and individual performance is partially mediated by centrality of the person in the network. Each of the constructs and relationships will now be described and anchored in the literature.

2.1. Role Characteristics and Individual Performance

Roles have been studied for over 60 years, dating from the early 1930s when sociologists and anthropologists attempted to explain social behavior (Linton 1936, Mead 1934). Role theory has emerged as a recognized discipline (Galletta and Heckman 1990, Biddle and Thomas 1966), and roles have been examined at societal, organizational, and group levels of analysis (Zigurs and Kozar 1994). Indeed, as Galletta and Heckman (1990) asserted, "the nature of organizations (and other social structures) is such that they can be understood in terms of the interactions and functional dependencies between individuals and groups" (p. 170).

Individual characteristics can be important, direct determinants of performance when their communi-

Figure 1 A Model of Individual Performance in Virtual Groups



cation is influential and when role and status markers are salient. In contrast to early research on computer-mediated communication, which suggested that individual characteristics are less influential in electronically mediated communication (Sproull and Kiesler 1986), more recent research found that when electronic communication is not anonymous, role and status markers can be salient (Zack and McKinney 1995). Our model reflects this in the direct link (arrow *c*) between individual role characteristics and performance.

Roles are important predictors of performance because they address "the degree to which individual behavior, social interactions, and the social person are constrained by social structure" (Stryker and Statham 1983, p. 311), and emerge from the "necessary division of labor" in an organization or group (p. 332). Constraints and division of labor have great potential to affect performance dramatically.

The individual role characteristics—functional role, status, and communication role—comprise the set of independent variables in our model, and serve to define three hypotheses involving direct effects on individual performance. Although the relationships between individual role characteristics and performance have not been tested in virtual groups, we will borrow empirical evidence from studies of traditional groups.

To make the discussion somewhat more tangible, we will adopt the context of the virtual R&D group, described more fully in a later section. The Soar group, engaged in a large software development task in an academic environment, is composed of faculty, senior researchers, paid staff, and graduate students. Soar members serve roles of developer or user,[1] and knowledge contributor or seeker.

Functional Role. The first individual role characteristic is occupational or functional role, which includes nonrelational (strictly individual) attributes such as activities that require specific skills. It is important to establish that functional roles do not need to be formal. For example, in the large software project studied here, individual volunteers from several organizations assigned themselves to roles that matched their skills and interests at any given point in time, there were no formal reporting relationships, and functional roles were not defined formally within the group.

Strong direct effects of occupational role on several performance variables were found in a study of 411 middle managers in three civil service occupational groups (Schmitt and Cohen 1989). The effects of occupational role far exceeded the effects of demographic variables, although some demographics were unevenly distributed among roles in the sample.

One likely underlying factor that could tie functional role to individual performance is the level of sustained resources that one can commit to the virtual group task. The large software project in our study involves members who devote sustained resources (for example, developers who are engaged full time in Soar R&D) to the project as well as those who have adopted more of a "part-time" role (for example, users who regard Soar as one of perhaps many tools

[1] There did not appear to be liaison or intermediate roles in the Soar community, where a "blurring" of functional role would exist. As §3 describes, analysis of mail messages helped resolve the role of the sender and/or receiver.

for their research). Therefore, developers are expected to exhibit higher Soar–related performance than users.

HYPOTHESIS 1. *In a virtual group, individuals in functional roles associated with sustained resources outperform those without sustained resources*.

Status. Status, sometimes measured by tenure and rank[2] (Salancik and Pfeffer 1977), is likely to have a direct effect on performance. However, the strength of this effect of status on performance might depend on the particular organizational or environmental context. Studies of traditional organizations have linked status directly with performance (Rossman 1997, Schmitt and Cohen 1989), particularly when related with R&D innovation (Fombrun 1978, Frost and Egri 1990). Status has also been linked with attitudes toward new technology (Rice and Aydin 1991), especially important in R&D organizations. Low-status individuals were poorer performers (Rossman 1997) and had more negative attitudes toward technology (Rice and Aydin 1991).

The direct effect could be explained by high-ranking individuals' possession of decision-making authority, enabling them to make decisions conducive to their work performance (Salancik and Pfeffer 1977). Rossman's explanation of a direct effect was that lower-status individuals had to negotiate two separate social organizations and that their official duties were regulated by administrators who have little knowledge of the actual work environments in which the duties were to be carried out.

HYPOTHESIS 2. *In a virtual group, individuals of high status* (*faculty members*) *are expected to outperform individuals of lower status* (*senior researchers and students*).

Communication Role. Communication role differs from functional role because the former is defined by (volitional) behavior rather than by task function, and members have greater control of their communication role over a short period of time. A group member can switch from an information-contributing role to a seeking role and back within minutes, but their less-fluid functional role tends to last years.

We suggest that in a virtual group, information-contributing behavior, rather than information-seeking behavior, will be associated with higher individual performance. The literature provides evidence that information contributing is related to expertise. Wasko and Faraj (2000) found that individuals with superior subject expertise in the virtual group's specialized knowledge are more likely to contribute knowledge. These same individuals are likely to be more productive due to their expertise. They also found that when members feel that their expertise is inadequate, they are less likely to contribute. The same sense of inadequate expertise will also prevent these individuals from sending their work to journals. Therefore,

HYPOTHESIS 3. *In a virtual group, individuals primarily contributing information are expected to outperform individuals primarily seeking information*.

2.2. Individual Centrality

An individual's centrality, or extent to which the individual is linked to others in the group, could be regarded as a measure of how closely he or she "belongs" to a virtual group. Central individuals exchange messages with a large number of members of a group. If an individual exchanges a large number of messages, it will not only change his or her own position in the structure, but others' relative positions as well, altering the entire structure (Carley 1991).

Centrality is a key measure in Social Network Analysis (SNA) (Rogers and Kincaid 1981), most appropriately used when communication structure is less strongly dictated by formal structures compared to traditional organizations (Rice and Aydin 1991). Research has found that virtual R&D groups over time seem to form their own informal, yet powerful network structure (Ahuja and Carley 1999).

SNA provides a more potent prediction of organizational behavior than formal structure (Krackhardt and Hanson 1993). Individual performance in traditional groups is often explained by various individual

[2] There are certainly other connotations of the word "status" that are also important but very difficult to measure. One connotation that is not considered here is reputational status, where individuals seek to maximize their influence and power within their status group, and even attempt to carry that influence and power with them as they move into other status groups. Instead, the more objective status groups of faculty, researcher, and student will be used in this study.

characteristics such as role (Schmitt and Cohen 1989), work experience (Galletta 1985), and gender (Rosenthal and Hautaluoma 1988). In virtual groups, salience and expression of these individual characteristics may be muted by distance, allowing the network position of an individual to exhibit stronger influence on behavior.

An individual's measure of centrality in a communication network has been empirically associated with several important variables that might lead to superior performance. Most important are influence (Burkhardt and Brass 1990) and cognition (Walker 1985), which are described more fully below; other variables beyond the scope of this study include attitudes towards new technology (Rice and Aydin 1991) and involvement in innovation (Ibarra 1993).

Individuals who are central can exert more influence by virtue of being linked with a large number of people in the network. They are more likely to be connected with other powerful actors in the network, potentially receiving information of higher quantity and quality than less central individuals. Centrality can also be viewed as a source of informal power. Like formal authority, it can translate into a high level of access to various resources (Burt 1982). The distinction between formal and informal sources of influence is that the latter arises from an actor's position in the actual patterns of interaction rather than a formally defined position in the organizational hierarchy (Monge and Eisenberg 1987).

Another performance-related factor that has been linked with network position is cognition. Network position was more important than function or product type in explaining differences in cognition (Walker 1985). Multiple cognitive explanations are available for the postulated relationship between centrality and performance. One explanation can be found in social information theory: Proximity to those who control relevant resources and information (Salancik and Pfeffer 1978) provides access to situational opportunities. Another is that an individual's structural context influences, or even determines, one's interpretations of events, perceptions, cognitions, and behaviors (Rice and Aydin 1991, Walker 1985). Individuals in structurally central positions can benefit from others' experiences and perceptions. Finally, communication theory tells us that network links help construct and communicate social norms and expectations (Rogers and Kincaid 1981). Being central enables a person to be aware of these norms and expectations and to some extent, perhaps, to even mold them according to one's abilities and interests.

2.3. Centrality as a Mediator

Besides direct effects of functional role, status, and communication role on performance in a virtual group, the model also includes indirect effects through structural position in the network (links *a* and *b* in the model[3]). The direct effects on performance imply that individuals have basic influence over others, due to factors such as status, previous interactions, or even potential interactions. The indirect effects assert that the individual characteristics also operate through an individual's measure of centrality.

While there are certainly strong potential effects of centrality on performance, centrality has its own antecedents. Examples found in the literature include education and expertise (Lincoln and Miller 1979), formal authority (Lincoln and Miller 1979, Miller 1986), and external work contacts or boundary-spanning activities (Miller 1986). Also, Ibarra (1993) showed that network centrality is determined by both personal and structural sources of power and in turn determines involvement in innovations.

In summary, although certain individual characteristics have been linked with superior performance, they present a rather incomplete picture of individual performance in virtual groups. For example, individuals of high status may not always perform better than those of lower status due to the limited reach of status in some cases (confined to a particular organization or subgroup), the individuals' lack of participation in

[3] One variable not included in this model is experience, usually measured as the number of years in a particular position. Our research site involved very new technology, and by definition the group's individuals were inexperienced across the board. We found that the number of years in the group, the only experience item that was available, was highly correlated with (occupational) status. The status variable therefore served as a surrogate for experience for this pool of data, and a separate experience variable was not included in our model.

the virtual group, or their unwillingness or inability to utilize their high status to gain centrality in the group. We propose that centrality may be a mechanism through which individual role characteristics indirectly affect performance in virtual groups; thus, it is hypothesized that the relationship between individual role characteristics and performance is mediated by centrality. Below we present a discussion of specific role characteristics and their impact on centrality and performance.

2.4. Individual Role Characteristics

Each of the same characteristics will now be discussed in relationship to the mediator, centrality.

Functional Role. We expect that, because of potential differences in information-processing needs, individuals playing different roles would exhibit different interaction patterns. Such differences have been found in both traditional (Barley 1990) and computer-mediated (Saunders et al. 1994) settings. These different patterns could include their levels of participation in group discussions, their levels of contributing and seeking information, and the individuals they target for their communications. For example, Soar users send periodic bug reports and inquiries when problems arise, and need to receive information about new versions of software and maintenance instructions. On the other hand, developers often play the role of "teachers" and therefore send to the group information regarding research problems on which they are working, code they develop to solve these problems, and fixes in response to bug reports.

The functional role of the message sender has implications on centrality. We expect developers to be more central because they have to communicate changes to a large subset of the user community, while users probably need to ask questions of only a few developers. Because the types of roles and their effects on centrality could vary across contexts (for example, in different industries, tasks, or types of virtual organization), specific directions of these effects are not predicted in this exploratory study.

Hypothesis 4. *In a virtual group, individual centrality mediates the influence of functional role on individual performance.*

Status. Several researchers have found status effects on information exchange behavior. Compared to individuals of lower status, higher-status professionals are more influential, communicate more frequently, use more sentences (Saunders et al. 1994) and interact more, even when considering other factors such as education, seniority, and gender (Cohen and Zhou 1991). Indeed, individual characteristics can influence communication patterns (Saunders et al. 1994, Cohen and Zhou 1991, Zack and McKinney 1995), and therefore may affect individual performance.

Status differences among group members have been found to affect group process, structure, resources, and performance. High-status individuals are likely to be valued by the group and are treated more tolerantly (Cohen and Zhou 1991, Saunders et al. 1994). Conversely, those low in status can sometimes be ignored even if their input is intelligent and creative (Torrance 1954). Higher impact and performance of high-status members of the group can also be explained by their access to more resources, higher immunity to social norms and peer pressure (Harvey and Consalvi 1960), and ability to work at an abstract, but not a concrete, level (Adelson 1984).[4]

Status may also have an effect on individual centrality (Morrison 1993, Rice 1987). Individuals with higher status in general should be more central. French and Raven (1959) have suggested that status confers legitimacy and translates into access to social capital. Also, because higher-status individuals generally have greater access to, and control of, relevant resources, and have more decision-making authority (Salancik and Pfeffer 1977), more people need to communicate with them regarding their work. Therefore,

Hypothesis 5. *In a virtual group, individual centrality mediates the influence of status on individual performance.*

Communication Role. In sharp contrast to traditional organizations where communication roles may be dictated or facilitated by formal structure, virtual group members can define their own information-contributing or seeking roles. Arguing for study of

[4] Besides higher ability to work at a concrete level, lower-status individuals were also found to be better able to differentiate the means to achieve long- and short-term goals (Walker 1985).

communication roles in a social network, Rice (1994) has suggested that information flows are important aspects of structure that are produced by the use of computer-mediated communication. In virtual groups, it is important that individuals be constantly aware of who in the group depend on them, and on whom they depend for important information (Drucker 1988).

In a virtual R&D group, contributing information may substitute for more traditional methods of establishing credibility usually found in co-located groups. It may allow people to develop contacts with those who are working in similar areas and place them in central positions in the network. Individuals contributing information might also become central in the group because those needing information seek them out for collaboration. By becoming central, these individuals are likely to perform better in the group.

HYPOTHESIS 6. *In a virtual group, individual centrality mediates the influence of communication role on individual performance.*

3. Data and Method

3.1. The Research Context: Soar

The Soar project group, initiated in 1982 at Carnegie Mellon University, is building a computer model and language to simulate learning and general intelligence (Carley and Wendt 1991), to provide general problem solving capabilities (Laird et al. 1987), and even allow us to "rethink more generally the current status of cognitive science and where it should be going" (Newell 1990, p. x).

Since the beginning, the Soar virtual group has been composed of corporate and academic researchers, serving both user and developer roles. The Soar group communicated extensively by e-mail, their primary communication mechanism, and considered the group as an important source for ideas, findings, and stimulation. Members had a common goal of advancing Soar as an architecture through research and development. Despite this commonality of goal, members were able to work independently on their individual tasks, involving widely disparate areas of expertise such as cognition, natural language understanding, and robotics, while being available to provide their expertise to others whenever called upon.

Over time, the Soar group became distributed extensively throughout the United States as well as Europe and Asia. In 1989, 18 research locations were represented, and by 1993, work had spread to 27 locations. Soar is not completely virtual, with clusters of individuals at each of a small number of locations. Given that a completely virtual group (one with no face-to-face interaction at all) might be a rarity, or even a laboratory concoction, the Soar group is perhaps an ideal setting for this study. Although Carnegie Mellon University provided a disproportionate cluster, other key participants were developers and researchers at Michigan and Stanford Universities. Seven corporations involved in the Soar project represented the chemical, manufacturing, aviation, and health sectors.

The performance of the group and its members can be evaluated in terms of their main R&D tasks, resulting in publications that showcase the accomplishments of the group. Because of the importance of these publications within the group, all Soar-related publications were reported to the archives. Also, because most of the Soar members were academic or corporate researchers, they were also rewarded for publishing the results of their work in their home institutions. Therefore, Soar-related publications are an unusually appropriate measure of productivity. A more detailed account of the Soar virtual group can be found in Ahuja and Carley (1999), which reports on another part of this study.

3.2. Social Network Analysis

Social network analysis is "a method of research for identifying the communication structure in a system, in which relational data about communication flows are analyzed by some type of interpersonal relationships as the unit of analysis" (Rogers and Kincaid 1981, p. 24). A communication network consists of interconnected nodes (individuals) linked by arcs or edges (communication flows), representing informal communication patterns that crystallize over time.

Data were collected through e-mail archives, member data archives, and informants. An e-mail archive

provided a unique opportunity to examine a large proportion of the group's significant communications, because any communications of substance were archived along with the mail. Therefore, information from important phone conversations, weekly face-to-face meetings, and semiannual workshops were included in the scope of our sample. According to an informant, the only discussions (among three principal investigators) kept off the list were related to budgeting and spending, which were handled in confidence.

The e-mail archive included all messages exchanged among Soar members during the summers of 1989 and 1993. Two distant periods of time were used to minimize limitations of examining performance and its determinants at a single point in time (Ibarra 1993) and to raise confidence that any findings are not attributable to one particular developmental stage or environment. The senior members approved the use of these e-mail archives for our research. Messages sent to the "official" Soar distribution lists were not included in our analysis because these lists were created specifically to disseminate information of general use and do not affect centrality measures.

Although the measure of centrality provided by social network analysis only focuses on the *pattern* of messaging and does not take into account the *reason* for messaging, the culture of the Soar group supported only messages that were useful, meaningful, and oriented toward the shared task. According to an informant, messages that failed to meet those criteria were ignored by the group and therefore would be unlikely to result in higher centrality, even in a relatively short period of time.

Of potential concern would be the extent to which messages sent to specialized lists were dropped. Analysis showed that most of the messages sent to those lists were also forwarded to the general "S-Group" archive, which are dropped for every member equally. Those that were not sent to the general archive reflected matters of an administrative nature and address items outside the scope of the Soar task. Examples include requests from Soar members to distribute documents, requests for information from nonmembers, and notices of software upgrades.

The other two sources of information were the Soar group member data archives and informants. The archives provided information on functional role, status, and the publications by each of the group members. Informants, key Soar members identified by one of the authors (also a member), provided information about member functional roles as well as Soar background and historical information.

3.3. Measurement

Functional Role. Developers were individuals who developed Soar code (in "Lisp" or "C"). Users were individuals who use Soar to build artificial intelligence models or applications. Ambiguous roles for three individuals in 1989 and two individuals in 1993 were resolved by interviewing the informants.

Status. In descending order, Soar members served in the capacity of faculty members, senior researchers, or students. According to an author informant, senior researchers were, in most cases, postdoctoral fellows in research units of corporations. Paid staff members were excluded from our analysis because they were mainly responsible for managing day-to-day operations and resources, and our goal was to study research and development performance, the primary Soar outcome. Although status was usually straightforward to assess, informants were interviewed when status was unclear.

Communication Role. Communication role was operationalized as information-contributing versus information-seeking behavior. Members send a variety of information types (announcements, questions, or responses) in their e-mail messages. We content-analyzed each message to determine to which of the three categories the message belonged. Messages represented information-contributing behavior when they made an announcement or responded to questions sent by an individual. Information-seeking behavior were represented by questions sent to others. The individual's communication role was the ratio of contributions to the questions he or she sent to the group. A ratio above 1 revealed that the individual contributed more than he or she sought. In contrast to functional role and status, communication

role was measured as a continuous rather than a discrete variable.

Such a metric is imperfect, in that individuals could achieve the same ratio in countless ways. For example, two individuals could achieve the same 1:1 ratio with one message sent and one received, or 10 messages sent and 10 received. Two methods of attempting to correct this problem are weighting some individuals more heavily than others and removing data points below an arbitrary level. We chose to retain all nodes above a minimum, "temporary visitor" threshold and preserve the ratio scale in this study, with the caution that this single measure does not tell the entire story; taken together with centrality and status measures, a more complete picture can be viewed.[5]

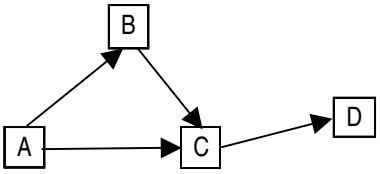
Messages were read and coded by one of the authors and one other coder. Every two weeks, for a total of 15 times, we randomly selected 30 messages from each coder's database and matched them. The intercoder reliability was consistently higher than 90%.

Centrality. Freeman (1979) proposed three separate measures of centrality, including degree centrality (involvement), distance centrality (power), and betweenness (information control). We were interested in a person's involvement in the group and therefore utilized the measure of degree centrality.

Degree centrality is based on the number of nodes (individuals) to which a node is adjacent (Scott 1991), or connected by an arc. A node is central if it has a higher degree than others in the network. The major limitation of this degree centrality is that it should only be used to compare centrality scores within a single network. However, this limitation was overcome by using scores standardized for network size.

[5] The danger is that the continuum does not necessarily range from "high" to "low." Most linear analysis would run into difficulties if a large number of intermediate (balanced) cases would exist. Fortunately, most members were easily categorized, and those who were balanced usually had a very small number of messages. Therefore, the effect of this bias was minimal. In future studies, however, researchers would perhaps need to plot the results and/or identify a lower threshold level for considering what is "high" versus "low," perhaps assigning a maximum score at a level above, for instance, sending 50% of what is received.

Figure 2 Nodes in a Small Network



An individual with low degree is isolated from direct involvement with most of the others in the network and is cut off from active participation in the ongoing communication process. A central person, on the other hand, is heavily involved in the network (Freeman 1979). In Figure 2, node C is most central because it is adjacent to three other nodes. Node D is peripheral because it is adjacent to only one other node.

Degree centrality is posited to relate to publication performance for two reasons. First, the number of links for a particular individual is likely to increase as the value and/or amount of information possessed by that individual increases. This larger base of knowledge would be natural fodder for publications. Also, each link represents an additional potential collaborator and/or coauthor. A large number of Soar publications were jointly authored, raising the probability that such collaborations would correspond to a large number of communications.[6]

To compute centrality, who-to-whom information was recorded for each of the selected messages in the form of social network matrices.[7] A social network matrix is a binary matrix that places senders

[6] Similar arguments have been made by Kilduff and Krackhardt (1994) for the use of degree centrality as an indication of influence. In this paper, we did not use proximity/distance and betweenness, as in this particular dataset the three measures are highly correlated, and only one measure was called for.

[7] There are alternative ways in which the networks of connections among people could have been constructed which would affect how centrality was measured. For example, we could have used the volume of messages or the total length of messages. Such variations might affect the outcome. In this particular group, however, message length did not appear to be a consistent indicator of role-based behavior. Moreover, people who sent to more people often tended to send more often. Further, the number of people that were interacted with is actually a better indicator of overall influence on the group than the volume of messages, as it uncovers the range of influence.

on each row and recipients on each column. If a link (one or more messages) between the two individuals is present, a 1 is placed into that cell. The absence of a link is represented by a 0.[8]

The social network software package UCINET IV (Borgatti et al. 1992) was used to convert these matrices into individual centrality scores. In UCINET, one can choose to treat data as symmetric or asymmetric while computing degree centrality. To preserve status asymmetry, we chose to treat our data as asymmetric, following Ibarra and Andrews (1993). This means that in computing centrality, sending and receiving are treated as distinct activities.

Performance. As described in §3.1, individual performance was defined as the output of an individual's efforts with regard to Soar. Because Soar is an interorganizational group (individuals are members of one organization while also members of the Soar group that runs across organizations), it was important to distinguish between individuals' overall performance from their Soar-related performance.

In a study of individual performance in a group setting, it is important to establish the consistency of group and individual goals. In this group, three goals were shared by both the overall group and its members: (1) advancement of artificial intelligence research; (2) making progress on the system itself (the Soar architecture) by completing the project effectively and improving the user interface; and (3) publication of incremental progress on the project. The latter goal was shared by the group because it served to bring visibility to Soar. The three goals were highly correlated—as visibility brought increased opportunity for funding, additional funding brought more resources to bear on the project, and additional resources made it possible to make progress more quickly, yielding more publications and visibility.

We considered several alternative measures of individual contribution to the common group goal of improving the Soar architecture. For example, we considered using the number of lines of code. However, there is a great deal of variance in the type of code (languages, tools, etc.) generated by developers and users. Because of tool and specific task differences, a large number of lines of code does not necessarily imply greater contribution. It was considered more feasible to examine the Soar-related publications, evaluating the quality as well as the quantity of the target journals.

Most of those members not employed by academic institutions were employed by research organizations or research units of corporations that also evaluated performance based on publications. Therefore, individual performance was measured in terms of the quantity (weighted by quality[9]) of Soar-related publications produced during the period of study and two years after the study period (to allow for writing and revision time of research reports). The Soar archives contain abstracts of all Soar-related publications by members, providing rather objective performance measures of group members. The group norm in Soar was to include only those individuals who took an active part in the research or writing, as coauthors, therefore coauthored papers received the same credit as single-authored papers for each of the authors.

3.4. Research Sample

All e-mail messages from the summers (June, July, and August) of 1989 and 1993 were included in this study. Summer months were considered appropriate because in the academic world, the most intense research is performed during this period of low teaching responsibility.

Although we wanted to include e-mail messages from all Soar members, we also wanted to refrain from including the casual inquirers in this study. Because a typical casual exchange consisted of one message of inquiry, one acknowledgement, and one descriptive message, we decided to include messages from all individuals who sent more than one message to the group and received more than two responses

[8] See Wasserman and Faust (1994).

[9] Quality of the publications was measured on a five-point scale (5 = top ranking journal, 4 = middle-tier journal, 3 = refereed conference proceedings, book chapters, and remaining journals, 2 = nonrefereed conference proceedings, and 1 = technical report or a working paper).

Table 1 Sample Size for Each Period

	Members	Messages
1989	53	1,126
1993	65	655

Note. 23 members are common to both time periods.

from the group. This selection process ensured that only the members with more than a casual contact with the Soar group were included in the study.

The size of the group in each sample is shown in Table 1.

The time lag of four years between the two study periods was chosen for a number of reasons. First, the composition of the group and therefore the structural position of group members could reasonably be expected to change considerably as a result of the death in 1991 of the founder of the Soar group, Allen Newell. Second, many active members of the group were students who progressed to graduate programs and postdoctoral fellowships, becoming senior researchers. Between 1989 and 1993 most of the students had changed their status. Also, the number of people who knew about the group and used Soar tools increased. Finally, improved methods of communication reduced the number of messages devoted to coordination of events and tasks (and appear to have reduced the overall number of messages dramatically). In the later period, frequently-asked questions lists were made available online, documentation was improved, and routines for allocating resources were adopted.

The distribution of authorship was very wide, suggesting that collaboration did not take place in private "blocks," which would require separate analysis. Also, a large proportion of the papers were authored singly (39%), and many papers were published by Soar members in collaboration with non-Soar members (19%). Nevertheless, the mean number of authors was 3.00, and the standard deviation was 4.91, suggesting that a large amount of collaboration took place, and therefore the virtual group made effective and frequent use of the communication network.

Table 2 Group Composition for Each Period by Role

	Users	Developers
1989	39	14
1993	45	20

Table 3 Group Composition for Each Period by Status

	Faculty	Senior researchers	Students
1989	12	10	31
1993	11	29	25

It is also important to establish that coauthorships did not simply include "co-located" publications (those where all coauthors represented the same formal institution). Not only was there substantial representation of "virtual" coauthors who worked with Soar members outside of their formal institutions, but the ratio of virtual member publications exceeded co-located publications by a factor of 1.3 to 1. Therefore, physical proximity was not the most important force in coauthorship.

Tables 2 and 3 show the composition of the Soar group during the two study periods. As can be seen from Table 2, the number of both users and developers increased between periods. Table 3 shows that while the number of students decreased, the number of senior researchers (including corporate researchers and postdoctoral fellows) more than doubled between the periods.

4. Results

Venkatraman (1989) has recommended using structural modeling to test mediating fit between variables. We tested the hypotheses using partial least squares (PLS version 1.8) analysis, a second-generation multivariate regression-based technique for the assessment and estimation of structural models (Fornell and Bookstein 1982, Wold 1982, Löhmoller 1984). PLS has been used as an alternative to LISREL analysis, which uses the covariance fitting approach for estimating structural equations, and employs a maximum likelihood estimation (MLE) procedure that places more rigid constraints on the data and requires a larger sample (Chin and Newstead 1999). PLS avoids many of these limitations by following a components-based strategy (Fornell and Bookstein 1982, Tabachnik

and Fidell 1989). While PLS accomplishes predictive accuracy (Chin 1998, Anderson and Gerbing 1988, Wold 1982), its parameter estimates are less than optimal for bias and consistency due to its information limitations. Also, because PLS makes no prior distributional assumptions about the data, it requires a resampling procedure for significance tests or to provide estimates of confidence intervals for path coefficients.

To estimate the significance of the path coefficients, we used a bootstrapping approach, where 100 random samples of observations (with replacement) were generated from the original dataset. The path coefficients were reestimated using each one of these samples. The resultant vector of parameter estimates was used to compute the parameter means and standard errors needed for computing the significance of the path coefficients. We replicated this approach with two additional iterations of 250 and 500 random samples of observations with replacement to assess the stability of the significance of the path coefficients. This overall approach has been recommended by Efron and Tibshirani (1993) and Chin (1998), and has become a standard practice in estimating the significance of path coefficients in PLS models (e.g., Ranganathan 2002, Mooney and Duval 1993).

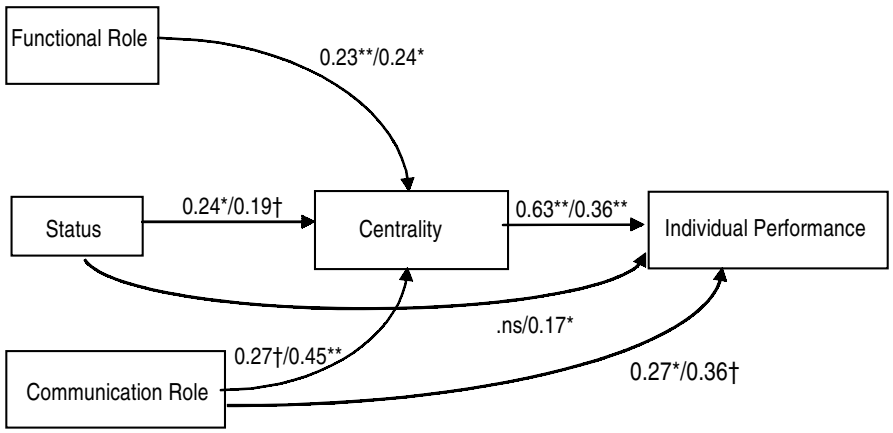
Figure 3 provides the path coefficients for both 1989 (left number) and 1993 (right number). Hypotheses 1 through 3 test the direct effects of individual role characteristics (functional role in Hypothesis 1, status in Hypothesis 3, communication role in Hypothesis 5) on performance.

Functional role did not have a direct effect on performance in 1989 or in 1993. Hypothesis 1 is not supported. Status did not have a direct effect on performance in 1989 but did in 1993, providing partial support for Hypothesis 2—higher-ranking individuals tended to have higher performance in 1993 than lower-ranking individuals. Communication role had significant direct effects on performance in both 1989 and 1993. (Contributors, seekers, and balanced individuals published 4.1, 0.9, and 1.0 articles, respectively, in 1989 and 3.5, 2.7, and 0.9, respectively, in 1993.) Hypothesis 3 is supported—information contributors tended to have higher performance than information seekers.

Hypotheses 4, 5, and 6 examined the mediating effect of centrality on the relationship of functional role, status, and communication role with performance, respectively. The path between centrality and performance was significant and positive in both years.

As Hypothesis 4 predicted, functional role had a significant effect on centrality in 1989 as well as in 1993; developers were more central and seemed to exhibit greater performance than users. The significant paths from functional role to centrality and centrality to performance imply that centrality mediates the relationship between role and performance. Therefore, Hypothesis 4 is supported.

Figure 3 Individual Role Characteristics, Centrality, and Performance (1989/1993)



Note. $^{\dagger}p < 0.1$; $^{*}p < 0.5$; $^{**}p < 0.01$.

The paths between status and centrality and centrality and performance were also significant in both years (both positive). Higher-status individuals were more central and, as noted before, central individuals were higher performers. Thus, Hypothesis 5 is also supported.

The effect of communication role on performance follows a similar pattern, with contributors being more central. Therefore, communication role's effect on performance is mediated by centrality of the individual, providing support for Hypothesis 6.

Given that communication role had significant direct as well as indirect effects on performance in both years, we conclude that there is evidence of a partial mediating effect of centrality on this relationship.

5. Discussion

Evidence from both study periods provides support for the assertion that an individual's performance in a distributed group is an outcome of the individual characteristics of functional role, status, and communication role, mediated by the individual's centrality in the group. Overall, centrality was a stronger direct predictor of performance than the individual characteristics considered in this study.

Functional role seemed to enable a person to achieve centrality in the group. Functional role did not affect performance directly, but did indirectly by influencing a person's centrality. Evidence from the 1993 sample suggests that the higher the status of the individual, the better performance is likely to be; faculty in the second study period performed better than students and senior researchers. However, a more consistent finding was that higher status was associated with greater centrality and higher performance. It is possible that the extent to which centrality mediates the effect of a particular individual characteristic on performance depends on the individual characteristic being studied and the level of maturity of the group.

Data from both 1989 and 1993 showed a strong relationship between the third examined role characteristic of individuals—communication role—and performance (Figures 3 and 4). The findings suggest that communication role is a more consistent predictor of performance in virtual R&D groups than are functional role and status. Thus, the manner in which an individual interacts with the virtual members of the group appears to be an important factor in determining the individual's performance in the group. Centrality also (partially) mediated the relationship between communication role and individual performance.

The findings related to communication role are important because, in contrast with functional role and status, communication role depends upon individual behavior. While members may not have any control over their functional role and status in the short term, they are likely to have volitional control over their behavior (and therefore their communicational role). Our results underscore the importance of distinguishing between volitional and nonvolitional individual characteristics in virtual groups.

We found that individuals who tend to contribute more information to the group than they seek will perform better. To further test the relationship of communication role and performance, we divided Soar members into those who are high or low seekers, and high or low contributors, and performed a two-way ANOVA with performance. Information contributing was a significant predictor of performance in 1993 while a two-way interaction was a significant predictor of performance in 1989.[10]

Many questions asked, "who knows how to do this?" or "what did you find out about this?" People likely to answer such questions were those with the knowledge to be communicated beyond the group in the form of papers. Sometimes questions led to the response, "I don't know, but I will figure it out," which in turn led to the production of an academic paper. Information contributing may be an indication of superior knowledge, expertise, and active involvement in the creation and pursuit of knowledge.

[10] In 1993, for low contributors, low seekers published 1.0 and high seekers published 0.95 articles. For high contributors, low seekers published 3.12 and high seekers published 3.8 articles. In 1989, for low contributors, low seekers published 2.0 and high seekers published 3.69 articles. For high contributors, low seekers published 6.29 and high seekers published 1.14 articles.

Because the work of this group was knowledge based, if information contributing is related to expertise it is likely to be related to performance. Further, the results of this study suggest that there might be a tendency for communicative activity in one medium (e-mail) to carry over into communicative activity in another (paper production). Additional research should be conducted to determine whether this effect applies to other virtual groups and other contexts.

Of course, performance would not be increased merely by sending more messages over the short-term. The culture of the group was that members tended to send only meaningful communications; all were politely asked to refrain from sending messages that did not contribute to the project. In general, therefore, the correlations represent collective acts, rather than individual acts, that fit the group's culture.

In the Soar group, members who contributed information were often senior members with heavy investment in the group and extensive expertise. Thus, apart from transferring knowledge, information contributing may be a mechanism that the core members of the Soar group utilized to facilitate the process of socializing new members in the group.

Unfortunately, the literature on socialization in traditional groups has found that information seeking is also associated with intention to leave (Morrison 1993). In a virtual group, where the goal of information contributing by senior members is that newcomers will, in time, become core members of the group, this pattern can be disturbing. We did not examine exit intentions or any relationships between those intentions and behaviors, but present such tests as an avenue for future research.

To explain the different status findings across the two time periods, we examined the changes that took place in the group over time. After the death of the founder, Allen Newell, between the two time periods, there was diffusion of leadership among a few key members of the group, corroborating with the lower centralization[11] score in 1993. It is possible that other factors associated with maturity of a group also account for a change in structure of the group over time.

Table 4 Centralization and Hierarchical Levels by Organizational Task (1989 and 1993)

	Centralization		Hierarchical levels	
Organizational task	1989	1993	1989	1993
Design	0.90	0.81	0.55	0.80
Resource management	0.83	0.82	0.55	0.66
Group maintenance	0.90	0.84	0.80	0.70

Another plausible explanation for the differences between 1989 and 1993 may be found in the way in which the group's network structure changed in 1993 (see Table 4). We examined the network structure of the group using communication network techniques of centralization and hierarchical levels[12] for various task networks (networks formed by e-mail exchange among people working on specific tasks). Details on the structure of these task networks in the Soar group, and their measurements, can be found elsewhere (Ahuja and Carley 1999). In 1993, the group showed more hierarchy (indicated by somewhat higher scores on hierarchical levels measure), but with less centralization than in 1989. A logical conclusion is that in this environment (created by more hierarchy but less centralization), status of an individual had a direct influence on performance, as is the case in traditional groups. This may imply that as virtual groups mature,

[11] Centralization refers to overall integration or cohesion of a network graph. Centralization indicates the extent to which a graph is organized around its most central point (Freeman 1979). A decentralized structure, at the extreme, is one that is fully connected and allows immediate feedback and error-correction (Tushman 1979). The particular measure we utilized is degree centralization. The degree of a point is shown by the number of arrows coming in or going out of the point in a graph (Freeman 1979). Conceptually, the degree of a point in the graph is the size of its neighborhood. This is measured by the aggregate difference between the centrality scores of the most central point and those of all other points. It is the ratio of the actual sum of differences to the maximum possible sum of differences. Degree centrality scores can range from 0 to 1, 0 being the score for a completely decentralized network.

[12] The hierarchical levels measure (Hummon and Fararo 1995) is based on an examination of the whole structure and reflects the number of levels one must go through to obtain information. An existence of hierarchical levels indicates that members must go through someone rather than directly obtain information from the source. More details on this measure can be obtained from Hummon and Fararo (1995).

they start behaving in a manner that is more consistent with traditional groups.

In summary, the findings support the assertion that an individual's performance in a virtual group is an outcome of the individual role characteristics mediated by the individual's centrality in the group.

6. Contributions

This study examines the relationships between individual role characteristics, centrality, and individual performance in a virtual group. The results provide evidence across two time periods that the centrality of an individual in a virtual group is determined by his or her functional role, status, and the manner in which he or she interacts with the group. These effects on specific functional roles and status are likely to vary with context as different functional roles and status types apply to the situation. However, in general the findings indicate that centrality can be, at least in part, predicted by functional role and status and that it is centrality, rather than individual role characteristics, that consistently and directly predicts performance. It appears that the extent to which centrality mediates the individual role characteristics depends on the particular context of the virtual group. Future studies should explore this relationship to better understand this mechanism of mediation.

This study extends the research in the areas of virtual groups to the R&D and software development environments. It provides a basis for theory building for this increasingly popular type of work environment. By building on this study, researchers can begin to address some of the issues related to virtual design groups, and increase their efficiency and performance. Researchers can also potentially build on this research to design specifications for computer support for virtual groups.

There are also implications for knowledge management; the finding that information contributors perform better individually implies that R&D group members have a self-interest in sharing knowledge. This is good news for virtual groups because by actively sharing their knowledge, experts can sustain the dynamics of exchange (Wasko and Faraj 2000). This linkage should be explored in more detail.

Single-group studies like this one are limited in the extent to which their findings may be generalized to other contexts. Although the findings might only apply to the Soar group, they provide some insights into the relationships between individual role characteristics and individual performance at two periods of time in a group's evolution. Similar studies in other settings can test whether the findings can be applied to virtual organizations in general. Beyond the particular group examined, the sample has very heavy representation from university-related individuals, and its results should not automatically be extrapolated to other samples, such as those in for-profit corporations. Fortunately, research and development organizations in a variety of settings share the academy's focus on research projects, publications, and presentations. Furthermore, the task is knowledge based, status differentials exist, and membership is dynamic as in other virtual groups.

Another limitation of the study is the lack of differential analysis of "balanced" communicators who sent and received few messages from those who sent and received many messages; too few fell into that category. Fortunately, in our case most participants fell clearly into either the role of seeker or that of contributor. Future research might develop a two-dimensional categorization scheme for exploring communication role identification with different R&D groups, especially in those with adequate samples in each cell.

Field studies are also limited by the fact that they have no control over the factors that might interfere with the phenomena under investigation. For example, economic, social, and organizational factors can interfere with group and organizational processes. However, comparing two datasets from the same group representing two different time periods has been likened to a quasi experiment in a natural setting (Lee 1987). A related limitation is that the lack of experience of organizations with e-mail during the period studied probably increases the variation of organizations' responses as they employ such communication tools for the first time. However, this difficulty is minimized in this study because the organizations represented already had been using e-mail quite heavily for over a decade before the sampling

periods, and their culture therefore included e-mail as a routine communication mechanism.

This study focused only on e-mail, excluding other modes of communication such as face-to-face meetings, phone calls, and letters. Fortunately, e-mail was the primary mechanism for group-related communications in this sample because of the geographic dispersion of the group, the low cost of e-mail, and its ability to include code segments or other attachments.

Finally, the measure of centrality ignored volume (over the "casual" threshold) and focused only on whether or not communication existed between two individuals. Similarly, the performance measurement included only one type of productivity. In an R&D group, other performance measures assessing the quantity and quality of software generated can also be important. However, such measures usually include significant challenges to interrater reliability, stability, and objectivity.

In spite of these limitations, this study offers many significant implications for R&D groups. The cooperative culture of Soar fostered sharing of ideas, valuing coauthored papers as highly as sole-authored papers, and giving due recognition to ideas of others even when the ideas had not been published. This culture was likely instrumental in encouraging the development of information contributors. Our understanding of other virtual groups can be informed by our results if they are similarly cooperative and also share many of Soar's other characteristics, such as its role and status differentiation, its focus on knowledge-intensive work, and its measurement of productivity through creation of knowledge. One might consider this as creating a culture of "networking" (Baker 1994). One possible mechanism would be to consciously create highly central personnel by placing talented and potentially innovative individuals on multiple teams and projects so that they can increase the number of people they know and to whom they can contribute information.

As organizations continue to experiment with, and adopt, new organizational forms that rely less on formal structures and more on informal mechanisms, researchers will need to understand the extent to which these informal mechanisms have direct influence on behavior and performance. Studies are needed that will investigate how these informal mechanisms, and in particular informal social networks, influence individual performance. This study was intended to provide an early step in achieving that understanding.

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