The Ecology of Team Science

Understanding Contextual Influences on Transdisciplinary Collaboration

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Abstract: Increased public and private investments in large-scale team science initiatives over the past two decades have underscored the need to better understand how contextual factors influence the effectiveness of transdisciplinary scientific collaboration. Toward that goal, the findings from four distinct areas of research on team performance and collaboration are reviewed: (1) social psychological and management research on the effectiveness of teams in organizational and institutional settings; (2) studies of cyber-infrastructures (i.e., computer-based infrastructures) designed to support transdisciplinary collaboration across remote research sites; (3) investigations of community-based coalitions for health promotion; and (4) studies focusing directly on the antecedents, processes, and outcomes of scientific collaboration within transdisciplinary research centers and training programs. The empirical literature within these four domains reveals several contextual circumstances that either facilitate or hinder team performance and collaboration. A typology of contextual influences on transdisciplinary collaboration is proposed as a basis for deriving practical guidelines for designing, managing, and evaluating successful team science initiatives.

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Introduction

The growing interest and investment in transdisciplinary team science over the past 2 decades are reflected in the establishment of several large-scale research and training initiatives by both public agencies and private foundations.[1–7] This increasing commitment to transdisciplinary collaboration in science and training stems from the inherent complexity of contemporary public health, environmental, political, and policy challenges (e.g., cancer, heart disease, diabetes, AIDS, global warming, inter-group conflict, terrorism), and the realization that an integration of multiple disciplinary perspectives is required to better understand and ameliorate these problems.[8–12]

The expanded investment in team science and training has prompted greater demands for evidence that they be cost effective and justifiable in terms of their scientific, training, clinical, policy, and health outcomes, especially relative to smaller-scale, discipline-based research projects.[13–16] Team science initiatives typically entail substantial multiyear commitments of monetary, human, and material resources.[17] Critics of team science contend that its value-added contributions to scholarship, training, and public health may not be evident for several decades and are exceedingly difficult to calibrate in rigorous experimental fashion relative to those yielded by smaller-scale, unidisciplinary projects (e.g., single-investigator NIH R01 grants).[18,19]

Even proponents of team science initiatives note that they are highly labor intensive; often conflict-prone; and require substantial preparation, practice, and trust among team members to ensure a modicum of success.[20–22] The labor-intensity of collaborative research programs may pose unique risks to young scholars who are particularly concerned about establishing strong scientific identities within their chosen fields.[23] Consistent with these concerns, a growing number of studies focusing on the processes and outcomes of transdisciplinary scientific collaboration suggest that the effectiveness of team initiatives is highly variable and depends greatly on certain contextual circumstances and collaborative readiness factors.[24–26] It is becoming increasingly clear that investments in team science are not uniformly cost effective, although they can be enormously valuable under the right circumstances (e.g., the cross-disciplinary collaboration of Watson and Crick on the structure of DNA, the Kennedy Administration's commitment to land a crew on the moon by 1969).[27,28]

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Considering the varying levels of effectiveness that have been achieved by transdisciplinary teams and research centers within the health sciences, it is important to better understand the contextual determinants of collaborative success as a basis for knowing when (and when not) to invest in large-scale team science initiatives.[29] In short, investments in transdisciplinary team science and training must become more strategic and cost effective in the coming years, especially in light of recent budget cuts, resource shortages, and the importance of ensuring that research investments will yield scientific and translational advances that directly ameliorate population health and environmental problems at national and global levels.[30]

Mapping the Ecology of Team Science

To establish a more-strategic basis for designing, managing, and evaluating team science initiatives (and deciding when to opt instead for smaller-scale, unidisciplinary approaches to health problems), this review examines the ecology of team science, or the complex web of intrapersonal, interpersonal, organizational, institutional, physical environmental, technologic (e.g., cyber), and other political and societal factors that influence the effectiveness of transdisciplinary collaboration in research, training, clinical, and public-policy settings. This ecologic analysis suggests a typology of contextual circumstances that jointly determine the effectiveness of transdisciplinary science and training. A key implication of the proposed typology is that investments in team science should be strategically targeted toward those research questions, settings, and teams that are most conducive to the collaborative success and long-term cost effectiveness of transdisciplinary initiatives.[31]

Identifying the most appropriate criteria for judging the effectiveness of transdisciplinary team science initiatives depends, of course, on the ways in which key dimensions of team performance and the essential qualities of transdisciplinary collaboration are defined. For instance, in the fields of social psychology and organizational behavior, the effectiveness of a team's performance is typically defined in terms of the quantity and quality of team products; the affective, behavioral, and cognitive influences a transdisciplinary team has on its members; and the team's capacity to perform effectively in the future.[32] Yet the evaluation of team science initiatives (defined as a unique form of intellectual teamwork) generally impose additional criteria of success. For instance, Rosenfield[33] contends that a *sine qua non* of effective transdisciplinary collaboration is the development of shared conceptual frameworks that integrate and transcend the multiple disciplinary perspectives represented among team members. Moreover, transdisciplinary conceptual frameworks are characterized as reflecting a higher degree of integration than is achieved through interdisciplinary collaboration.[34–36] The least-integrative forms of cross-disciplinary research, according to Rosenfield,[33] are multidisciplinary projects in which participating scholars remain conceptually and methodologically anchored in their respective fields (although by definition some sharing of diverse perspectives also occurs in multidisciplinary research).

In contrast to Rosenfield's definition of transdisciplinarity, the NIH Roadmap initiative[4] treats the terms *interdisciplinary* and *transdisciplinary* as basically equivalent and, for simplicity, focuses on the promotion of interdisciplinary collaboration. Within the Roadmap initiative, interdisciplinary research is defined as that which ". . . integrates the analytical strengths of two or more often disparate disciplines to create a new hybrid discipline."[4] Examples of hybrid fields spawned by interdisciplinary health research are cognitive neuroscience, behavioral medicine, psychoneuroimmunology, bioinformatics, pharmacogenetics, proteomics, nanotechnology, and populomics.[37,38]

In the ensuing discussion, the distinctions among multidisciplinarity, interdisciplinarity, and transdisciplinarity posited by Rosenfield and endorsed by others are retained, because these terms define collaborative effectiveness along a continuum of scientific achievements rather than in terms of a dichotomy between the emergence or non-emergence of a hybrid scientific field.[13,14,21,36,39] For example, the development of a shared conceptual framework among members of a transdisciplinary research center can be viewed as an important, albeit incremental, collaborative milestone, even if it is only one of many intellectual precursors that eventually cumulate in the form of a newly recognized hybrid field. If the effectiveness of team science were defined solely in terms of the emergence of new hybrid fields, then many near- and mid-term collaborative scientific achievements would remain undetected in the evaluation of team initiatives. Thus, it is important to account for the temporal sequence of transdisciplinary collaborative outcomes (e.g., from the early development of integrative conceptual frameworks to the subsequent emergence of new hybrid scientific fields) in the evaluation of team science initiatives.

Generic and Project-Specific Criteria for Gauging the Effectiveness of Transdisciplinary Collaborations

The contrasting definitions of cross-disciplinary research (e.g., multidisciplinarity, interdisciplinarity, and transdisciplinarity) presented by Rosenfield and the NIH Roadmap initiative (and the alternative criteria for judging the effectiveness of transdisciplinary collaborations) are generic in the sense that they are intended to apply to broad categories of similarly organized initiatives and programs (e.g., National Cancer Institute

transdisciplinary research and training centers). However, when diverse team science programs are compared, it becomes apparent that they often assign different priorities among the multiple potential outcomes of transdisciplinary collaboration. For instance, team science initiatives such as the NIH Clinical Translational Research Centers and the Centers for Population Health and Health Disparities emphasize strategies of community-based participatory research (as well as basic medical and behavioral research) for achieving effective collaboration among university researchers and community-based health practitioners as they work together to design and implement evidence-based disease-prevention programs.[30,40,41] Other team science initiatives, however, place less emphasis on the translation of scientific research into clinical practices and give higher priority to scientific discovery and intellectual integration. Thus, in addition to considering the generic criteria of transdisciplinary collaborative success, it is also essential that the evaluation of team science programs take into account their diverse, project-specific goals, ranging from the achievement of scientific advances and the education of transdisciplinary scholars to the translational, clinical, and public-policy benefits that accrue from investments in transdisciplinary research and training. To be maximally useful, the evaluation of team science initiatives should incorporate metrics that give the greatest weighting to the highest-priority goals (e.g., scientific, training, translational, policy) specified at the outset of each initiative by major stakeholder groups (e.g., funding agencies, principal investigators, community organizations, elected officials).[17,29]

At the same time, the content and priority ranking of collaborative goals may change over the life course of an initiative. For instance, the initial stage of a team science project may give the greatest emphasis to basic research and training, whereas the intermediate and long-term phases of collaboration may assign greater importance to the translation of scientific knowledge into community interventions and policies designed to improve public health. Thus, the substance and relative importance of an initiative's major goals may be phase-specific.

Clearly, any discussion of the ecology of team science must address the complexities inherent in selecting criteria for gauging the effectiveness of transdisciplinary collaboration, including those mentioned above. The typology of factors that influence the effectiveness of team science, presented in a later section of this paper, recognizes that the definition of effectiveness and the identification of highest-priority goals will vary somewhat among different research and training programs and across their different phases, and that the design, management, and evaluation of transdisciplinary initiatives must be tailored to address the unique and highest-priority goals of each. Moreover, multiple stakeholder groups (e.g., researchers, funders, community members) may define the highest-priority goals of a transdisciplinary program differently, thereby creating yet another challenge to the design, management, and evaluation of team science initiatives, as discussed below.

Review of Empirical Research on Team Performance and Transdisciplinary Collaboration

This analysis of contextual factors that influence the success of transdisciplinary collaborations is guided by empirical evidence drawn from at least four areas of scientific research: (1) social psychological and management research on the effectiveness of teams in organizational and institutional settings; (2) studies of cyber-infrastructures (i.e., computer-based infrastructures) designed to support transdisciplinary scientific collaboration; (3) field investigations of community-based coalitions for disease prevention and health promotion; and (4) studies focusing explicitly on the antecedents, processes, and outcomes of effective collaboration within transdisciplinary research centers and training programs. These areas were selected for review because they all identify key factors that facilitate or constrain teamwork across a variety of institutional and community settings. At the same time, the four research domains differ from each other in certain conceptual and methodologic respects. For instance, social psychological studies of team performance have relied heavily on short-term, laboratory-experimental investigations of randomly composed groups, whereas those in the fields of organizational behavior and management science more often have employed longitudinal field research to evaluate the functioning of pre-existing teams in corporate and other naturalistic settings.[32,42–44] Also, the criteria used to assess collaborative effectiveness vary widely, depending on whether the groups under study are randomly assembled and instructed to work on short-term experimental tasks or are longer-standing, self-selected teams employed by ongoing organizations to achieve specified financial, health, or intellectual outcomes.[45] Thus, university–community coalitions collaborate to promote population health, improvements in environmental quality, and social justice within a local community, whereas transdisciplinary science and training programs often place greater emphasis on intellectual discovery and scientific advancement as the most-highly prized collaborative outcomes.[29]

The four research domains reviewed below vary not only in terms of the kinds of teamwork studied within each, but also in the breadth or scope of collaboration examined in each field. Cross-disciplinary collaborations can be compared on at least three dimensions of integrative scope: organizational, geographic, and ana-

lytic, each ranging from narrow to broad.[29] The organizational scope of transdisciplinary collaboration includes **intra-organizational partnerships** in which participants work together within a single organization; **inter-organizational alliances** whose participants span multiple organizations; and **intersectoral partnerships** in which members representing multiple communities, regions, or nations form alliances to develop programs or policies covering larger geographic and political domains. For instance, studies of team performance in the fields of social psychology, organizational behavior, and management science predominantly emphasize an intra-organizational perspective, whereas research on university–community coalitions for health promotion encompass inter-organizational and intersectoral contexts of collaboration.

Similarly, the geographic scope of transdisciplinary collaboration ranges from local groups to community, regional, and national/global contexts of collaboration. Scientific teams, for example, include those based solely at a single locale (e.g., a university or research institute) as well as those whose participants collaborate across multiple, dispersed locations, often using electronic support systems to facilitate their communication.[46]

Finally, the analytic scope of transdisciplinary collaboration ranges from molecular (e.g., neuroscience) to molar (e.g., public policy) levels of intellectual analysis, depending on the nature of the scientific or community problems addressed by the team. As intellectual analyses move from molecular or cellular levels to community and policy perspectives, a wider range of academic and professional vantage points must be bridged to achieve a transdisciplinary approach to the problems at hand.[26] Generally, transdisciplinary collaborations encompassing broader organizational, geographic, and analytic scope face a larger and more complex array of potential coordination constraints as they pursue their scientific and community problem-solving goals.[29]

Differences in the kinds and scope of transdisciplinary collaborations studied within diverse fields suggest that extrapolations among the findings reported in each domain must be drawn with caution. A major goal underlying this analysis of transdisciplinary collaboration is to develop a typology of circumstances that constrain or enhance the effectiveness of team science and training programs. When the relevance of findings from social psychological and management studies of team performance for understanding transdisciplinary science initiatives are considered, for example, it is important to remain mindful of the differences between experimental teams studied in laboratory settings, on the one hand, and community-based coalitions and research organizations examined through naturalistic field research, on the other; or between assemblages of independent-minded scientists working in university settings compared to members of corporate teams that report directly to a single company boss. Nonetheless, certain contextual factors are consistently identified as important correlates or determinants of collaborative success across several research areas, as noted below. In this paper, particular attention is paid to these widely observed, high-leverage variables in developing a typology of contextual factors that influence the effectiveness of transdisciplinary collaborations. With those caveats, a review of empirical evidence drawn from four relevant research domains begins below.

Social Psychology and Management Research on the Effectiveness of Teams

Experimental studies of group dynamics and interpersonal processes (e.g., leadership, conformity, conflict) conducted in laboratory settings have been a focal area of social psychological research over the past six decades.[42–44,47,48] As concerns have grown in recent years about improving collaboration among members of community-based organizations, field research on teams working in and across specific organizational settings has expanded as a basis for better understanding how successful teams[a] work and what factors determine their effectiveness, such as team members' familiarity with each other, their social cohesiveness, group size, and leadership styles.[50–52] Empirical findings from this research are outlined below. Although the relevant literature is quite extensive, space constraints necessitate that the review of this earlier work be selective rather than exhaustive.

Team Members' Familiarity and Social Cohesiveness

Recent reviews of research on team effectiveness suggest that increased familiarity among team members as well as greater social cohesiveness lead to increased productivity.[32,45] Relatedly, it has been observed that social cohesiveness is enhanced in part by good performance itself.[45] In many organizational settings, strong network ties are more likely to form among members who share similarities in various demographic and educational criteria than among those who do not.[53]

[a]It is noted that distinctions have been drawn in social psychological and management research between the terms teams, groups, task forces, and their various subcategories (e.g., project teams, top management teams, production teams, action/involvement teams). However, these differences are not essential for purposes of this discussion, because all of the terms refer similarly to collections of interdependent individuals who share responsibility for outcomes and are recognized as distinct social entities by their members and outsiders. Moreover, because this study's purpose is to review the literature across disparate fields and to establish emergent themes relevant to transdisciplinary collaboration, the term *team* will be applied to all forms of collaboration examined in social psychology and management research.

Some studies have found that homogenous teams, although more socially cohesive, do not perform as well as heterogeneous teams on certain kinds of tasks, especially on creative and intellectual tasks.[54–56] Katz observed that familiarity among team members had a negative effect on team performance with the passage of time, suggesting that temporal factors play a crucial role in members' efforts to establish and sustain high levels of performance.[32,57] A recent experimental study assessed the effect of time on team performance under two conditions—one in which members were familiar with each other and another in which they were not—and found that, over time, initially unfamiliar team members performed just as well as the other team whose members were more familiar with each other at the outset.[58]

One explanation of the declining performance of teams whose members are familiar with each other is that, as familiar group members become more cohesive over time, interpersonal processes that diminish performance, such as social loafing[b] and "groupthink,"[c] intensify as well.[60–62] Another explanation is that communication among members declines as teams age.[57] Okhuysen[63] found that familiar teams exhibit less flexibility for change compared to teams of strangers, thereby jeopardizing their performance. Teams that are able to adapt to fluctuating task demands are more likely to be effective, because these environmental challenges prompt members to evaluate their current strategies and abandon ineffective ones.[64] Familiarity, however, may lock members into ineffective strategies over time because of their reluctance to modify preestablished roles and patterns of interaction.[63] Convergent evidence for the inverse link between familiarity and performance over time emerged from a field investigation of interdisciplinary scientific networks,[1] a topic discussed more fully in a later section.

Team Size and Physical Environmental Conditions

The effects of team size on performance are mixed, with some studies indicating that large teams require more coordination and time to reach decisions,[65] and others finding that teams, even with as many as 30–40 members, can achieve higher levels of performance because of their access to greater resources—especially time, energy, money, and expertise—for task completion.[49,66] Stewart's meta-analysis[67] examined empirical links between differences in team size and performance levels among teams working on complex tasks in uncertain environments and found a small but positive effect of team size on performance.

However, another study[68] of 15 interdisciplinary treatment teams in a hospital setting (where group sizes ranged from 5 to 12 members) found that overall effectiveness, measured by cohesiveness, meeting hospital standards, and the personal well-being of team members, was greater among smaller teams. That study also found that high levels of interdisciplinary collaboration were linked to greater cohesiveness which, in turn, contributed to improved performance. Moreover, members' ratings of physical environmental conditions at work, such as the availability of quiet and comfortable places for team meetings and adequate materials for discussion, were positively related to reported levels of interdisciplinary collaboration. The influence of a team's physical environment on patterns of collaboration also has been observed in earlier studies of corporate teams and university-based research centers.[13,26,69–71]

It is important to note that the optimal team size for enhanced performance is likely to vary, depending on the kinds of teams and organizations under study. For example, in a study of interdisciplinary research and training centers, Rhoten[25] found that smaller (<20 investigators) and medium-sized (21–50 members) centers were more conducive to the generation of interdisciplinary knowledge than larger centers (>50 investigators). Yet in other settings such as corporate departments, 20-member teams may be regarded as large rather than small. The relationships between membership size and performance quality thus are conditioned by the unique goals of particular teams and the ecologic contexts in which they function.

Leadership Traits and Behaviors

Earlier studies[17,29,72] of transdisciplinary research centers and teams suggest that leaders substantially influence collaborative processes and outcomes. Yet empirical links between the specific traits and behaviors of leaders and the effectiveness of team science initiatives remain to be drawn. There is, however, a long tradition of research on leadership, group performance, and organizational effectiveness within social psychology and management science, some of which is rooted in Max Weber's conceptualization of charismatic leaders.[73] For instance, research in these fields has identified various personal traits, such as intelligence, self-confidence, physical appearance, educational status, task-relevant knowledge, and sensitivity to members' socio-emotional needs, that contribute to effective leadership in team situations.[74–77]

[b]In the social psychology of groups, the social-loafing effect has been defined as a situation in which people expend less effort when working in groups than when working alone. One explanation is that people can get away with poor performance in groups because their individual outputs are not identifiable. Another is that they expect the other group members to loaf, and therefore lessen their own efforts to establish an equitable division of labor.[59]

[c]When group members try to reach consensus or minimize conflict without critically analyzing and evaluating ideas, either to avoid angering other group members or avoid being seen as foolish, they are exhibiting *groupthink*.[60]

Recent studies have moved beyond analyses of specific leadership traits toward a broader focus on the combinations of skills, patterns of behavior, and interpersonal styles exhibited by exemplary leaders.[78,79] According to Collins,[80] for example, it is the paradoxical blend of personal humility and strong professional will that enables some individuals to become exemplary leaders. Bennis[52] suggests that the leaders of "great groups" excel at generating and sustaining trust; cultivating a shared dream among members that provides them with direction, meaning, and hope; and have a bias toward risk taking and action. Similarly, the term *transformational leader* has been used in other studies[50,67,81] to describe individuals who are able to enhance fellow-members' motivation and performance by offering them a strong vision of collective success, bringing out the best in each member and empowering her or him to reach personally and collectively important goals. Teams rated higher on transformational leadership see themselves as more potent and achieve higher levels of performance.[81]

An important direction for future research is to examine the contextual influences on leaders' effectiveness within complex team science initiatives. As the organizational and geographic scope of transdisciplinary collaboration increases (e.g., for multisite initiatives), leadership responsibilities often must be shared and coordinated among multiple directors (e.g., those having primary responsibility for scientific, financial, and administrative leadership) located at geographically dispersed sites[29,72]—a topic discussed further in a later section of this review.

Participatory Goal Setting and Communication Patterns

Participatory goal setting is thought to enhance team performance by encouraging feelings of inclusiveness among team members and providing them structure, connection, and shared beliefs, as well as enhancing collective efficacy.[45,61,82–84] Importantly, the presence of a goal, compared to no goal or ill-defined goals, tends to elevate team performance by raising member effort and stimulating communication and cooperation.[32] Team-development strategies such as experiential learning and appreciative inquiry have been found to be useful in facilitating members' efforts to reach consensus about shared goals and aspirations.[50,61,85,86]

Communication has been a topic of long-standing interest in research on group dynamics. The lack of adequate feedback and communication is a major impediment to effective team performance.[61,86] Regular group communication involving the exchange of organization-relevant knowledge among employees was found to enhance innovation in a longitudinal study of manufacturing firms.[87] Good communication among team members encourages feelings of trust and psychological safety,[88] and enables teams to better manage issues of size, compatibility, and cohesion.[61] In a study of new-product team managers in a high-technology firm, Ancona and Caldwell[89] demonstrated that not only internal communication (communication among team members) but also external communication (communication beyond the teams) enhances performance. The use of group brainstorming to promote communication and idea generation also has received support, especially for teams communicating electronically.[32,45,46] The issue of effective communication for remote collaboration is discussed further in the section on electronic communication among spatially dispersed teams.[46,90]

Task and Outcome Interdependence

An additional factor that has been shown to influence team performance is the structural interdependence of members' tasks and rewards. An example of an interdependent task is software development, which requires a team consisting of programmers, quality-assurance experts, business analysts, and project managers to accomplish the task. An interdependent reward system is one in which all members are assessed and rewarded equally based on the performance of the team, regardless of variations in individual excellence. When researchers work collaboratively on a shared enterprise but pursue part of the project independently, they are said to be a *hybrid* team. Accordingly, members tasks and rewards have both individual and collective elements.[91]

In a study[91] of 150 teams of technicians in a corporation, it was found that teams perform best when their tasks and outcomes are either purely group-oriented or purely individual-oriented. Higher levels of task interdependence resulted in higher levels of cooperation, helping, and learning behavior, and demonstrated high-quality social processes. Similarly, group-reward systems for highly interdependent teams motivated members to perform well and resulted in greater effort. Hybrid teams, however, performed poorly, exhibited poor interpersonal processes, and had low levels of member satisfaction.[91]

These findings pose implications for the design of transdisciplinary research collaborations, notwithstanding the differences between corporate and scientific settings. Because transdisciplinary team science requires a high level of cooperation to achieve knowledge integration across disciplinary boundaries, it would seem advisable to organize research tasks so that they are structurally interdependent; encourage sustained collaboration through institutional, environmental, and technologic supports; and reward collaborative processes and achievements through an interdependent incentive system. Organizational structures that have hybrid or very low levels of interdependence have

been shown to produce low levels of interaction among members and to prevent the development of collective norms and mutual learning.[92] At the same time, excessive structural interdependence in research settings, especially when not supported by organizational, environmental, and technologic resources, can become problematic, as much time and effort must be spent on coordination issues rather than on the task itself. To be maximally effective, team science initiatives may require a balance between interdependent task and reward structures on the one hand, and opportunities for autonomous or semi-autonomous teamwork on the other.[67,78,93]

Team Effectiveness in Remote Collaboration

Remote collaboration refers to those arrangements in which team members are geographically dispersed. Spatially (and often temporally and culturally) separated teams of workers collaborate on scientific or managerial projects through the Internet and by using other information and communication technologies. New terms such as *scientific collaboratories* (the terms *virtual teams* and *distributed collaboration* are also found in the literature)[46] have come to represent network-based facilities and organizational entities that span large distances to allow contact among researchers, access to data and instruments, and the sustained interaction required to accomplish research tasks.[94–96] Remote collaboration can be intra- or inter-organizational as well as intersectoral in scope, depending on the particular context of collaboration and its specific purpose. The geographic scale of remote collaboration may be quite broad, as members often communicate with partners located in other countries. Distributed collaboration poses unique challenges for team effectiveness. A small but steadily growing body of work has examined the conditions that facilitate and constrain the performance of spatially and temporally dispersed teams. These facilitative and constraining factors are categorized as technologic, environmental, socio-cognitive, and emotional.

Technologic Factors

The availability of adequate infrastructure—such as the requisite bandwidth for distance technology tools (e.g., digital video and high-quality audio); state-of-the-art workstations; and the availability of technical support—is critical to the scientific and managerial success of distance collaboration. Olson and Olson,[90] for example, describe how a team of manufacturing engineers in Europe encountered difficulties while explaining a manufacturing issue to design engineers in the U.S. because they used only audio technology rather than both audio and video. The high costs and increased expenditure of time required to initiate and synchronize applications like data conferencing often curtail their use (e.g., broadcasting slides only briefly and reducing collaboration over joint work).[97] Because scientific and managerial collaborations require the transfer of large amounts of data securely and quickly, even synchronously, the additional challenges of maintaining data security, integrity, privacy, and long-term archival access often arise.[72]

Apart from these technologic infrastructure-readiness factors, conditions of technology readiness also have been addressed.[90] Observational studies of scientific and industrial collaboratories have found that users unfamiliar or inexperienced with the use of advanced technologies are not prepared for such forms of collaboration. Technology readiness also requires users to have adapted to the habits and patterns of technology use, such as preparing for and setting up meetings, having regular access to technology, and making information accessible to others in a timely fashion.[90] Assessing the technology readiness of participants before implementing distance collaboration is crucial for ensuring its success.

Environmental Factors

Technology-mediated collaboration changes the way people interact with their socio-physical surroundings. Tacit behaviors taken for granted in face-to-face transactions become major impediments in remote collaboration. Teams using tools for audio conferencing, video conferencing, or both, encounter difficulties such as being unaware of other participants' identities, the topic of discussion, the identity of speakers, and the mental and emotional states of their remotely located partners.[90] Distance collaborators must adapt to the loss of shared physical settings and socio-spatial cues. For instance, it becomes critical for dispersed team members to be explicit about information that is normally tacit in collocated teams to ease the collaborative process.[98] Another adjustment that may facilitate remote collaboration is the use of technology-mediated communication only for unambiguous activities that do not require frequent interaction and feedback (e.g., data collection versus idea generation or designing).[90,98]

An additional constraint faced by virtual teams, especially in international collaboration, is working in different time zones.[99] If coordinated well, work could proceed 24 hours a day, leading to increased productivity. However, working across multiple time zones means that team members are in different stages of their circadian rhythms—members of the U.S. team, for example, could be groggy early in the morning while simultaneously their French collaborators would be alert in the late afternoon.[90] Managing cultural differences poses other challenges for global teams. Misunderstandings due to linguistic differences, dispar-

ities in management styles, and status conventions in different cultures can constrain the effectiveness of global teams.[90]

Socio-Cognitive and Emotional Factors

Building and sustaining trust are perhaps the most crucial conditions virtual teams must achieve to be successful. Trust is especially fragile and transient in virtual teams, as members do not share a common socio-physical context, norms, values, or expectations, nor do they have opportunities to monitor each other's behavior.[100,101] An experimental study of computer-mediated teamwork found that lack of trust is a major constraint on performance, especially when teams engage in risky activities and have few shared experiences to rely on. Initial face-to-face contact and socialization were found to increase the trust levels among team members, facilitate the formation of social norms, and aid the establishment of group identity.[102] Face-to-face contact early-on may be a prerequisite for successful remote collaboration.

Effective and sustained communication among geographically isolated team members emerges as another essential element for creating common ground as a precursor to trust among collaborators.[90] Jarvenpaa and Leidner[100] found that increased social communication, along with task-related communication, strengthens trust. Communication expressing enthusiasm and optimism explicitly was found to facilitate the establishment of trust early-on in a collaboration. Teams that had high levels of trust exchanged many messages for clarification and to garner consensus on the task. They also initiated more communication and provided timely substantive feedback to fellow members. Enthusiastic and motivated leadership was another key factor that differentiated high-trust from low-trust virtual teams.[100]

Specific interventions found to improve distance collaboration include the presence of a technology facilitator to help resolve technical problems and a virtual-meeting facilitator who mediated discussions among the remote parties.[90,97] When multiple locations are involved, the presence of a site coordinator to handle location-specific administrative issues was found to improve communication among parties.[103] The creation of formalized communication conventions might include protocols for turn taking and the use of common specialized vocabulary among sites.[90] In addition to organizational strategies for improving interaction among dispersed team members, technologic advances also can ease some of the difficulties inherent in remote collaboration. For instance, technologically enabled group performance support systems, including tools for electronic brainstorming, evaluation, and voting, as well as exchanging comments, can assist virtual teams with decision making, resource planning, and other collaborative activities.[104]

Remote collaboration creates new expectations, alters roles, and shifts communication patterns for its members.[98] It therefore requires participants to make various social, organizational, and physical environmental adjustments and adaptations to new tools and technologies.[105] The success of both collocated and virtual teams is likely to be influenced by the collaboration readiness of its members and participating organizations.[26,90] Organizations and teams that lack a culture of sharing and collaboration are likely to resist change and remain ineffective. Moreover, if incentive structures are not aligned to encourage the adoption of collaborative tools and related behaviors, such behaviors are not likely to occur. Finholt[98] suggests that team members establish formal conventions about how data are to be used and credit shared at the outset of their collaboration to enhance its effectiveness. Another activity that can facilitate remote teamwork is the longitudinal evaluation of collaborative processes and outcomes (e.g., Teasley and Wolinsky[106]). Formative evaluations can lead to refinements in research and training programs, strengthen social networks, and encourage new organizational forms to emerge.[26,94,106]

Team Effectiveness in Community Coalitions

Community coalitions between scientists and practitioners translate scientific findings into interventions and programs that promote public health and social justice. These collaborations are usually inter-organizational in scope. The scale and complexity of transdisciplinary collaboration among researchers and practitioners increase further as the goals become broader-gauged with the design, implementation, and evaluation of health programs and policies spanning local, regional, national, and international levels. Such broad-gauged collaborations are intersectoral in scope.[29] Community coalitions are prone to the difficulties inherent in teamwork (such as conflict and social fragmentation) because of the complexity of their goals and environmental contexts as well as the diversity of participants' world views and educational backgrounds. Factors that can facilitate or constrain the effectiveness of community coalitions are noted below.

Identification of Common Goals and Outcomes

Contributing to both community concerns and research goals is a defining feature of transdisciplinary action research. Citizen groups, practitioners, and researchers bring diverse and often competing interests and problem-solving agendas to their partnerships.[29] At times, the expectations and priorities of funding agencies are different from a coalition's goals, imposing

additional collaborative constraints.[107,108] An evaluation of the first 4 years of an intersectoral community coalition identified as a key challenge the achieving of a balance between community interests and research needs.[108] Whereas practitioners' goals are more pragmatic, community-oriented, and favorably disposed to quick decisions and the implementation of problem-solving strategies, researchers generally have a longer-term orientation, are more concerned with basic research questions, and aspire to publication and the receipt of grant funds.[29,107] Conflicts also may arise from differences in ethical practices and beliefs about what constitutes a realistic timeline to achieve the coalition's goals.[72] Coalitions whose members endorse competing goals and outcomes; hold different views of science and society; and use dissimilar terminology, language, and decision-making styles are likely to experience conflicts that undermine the team's performance. Coalitions that identify clear goals and objectives perceived to be attainable, agree on shared research-principles, and reach consensus on major areas of concern face fewer collaborative challenges.[29,107–109]

Distribution of Power and Control

The inequitable distribution of resources (e.g., information, time, funding, decision-making power, participation, and control over aspects of the community problem-solving process) is a major impediment to coalition progress and sustainability. Perceived status differences—between scientists and practitioners, and between health professionals and community members—can prevent collaborations from achieving their goals.[29,107–110] Other studies of coalitions highlight the importance of the continuity of collaboration between researchers and practitioners over extended periods and across the various phases of action–research, including the formulation of goals and the translation of research into preventive and therapeutic interventions, scientific publication, and community empowerment.[29,108,111] The joint development of operating norms that encourage open communication, mutual respect, inclusiveness, and shared decision making also facilitate the collaborative process.[107,108]

History of Collaboration

Building on prior positive experiences with a certain organization or community enhances trust among coalition partners and is a practical strategy for strengthening future collaborations. A lack of trust and respect arise from prior collaborations in which community members perceived no direct benefit or even harm, or if they received no feedback.[107,112] Groups in the U.S. that have experienced historic oppression, such as Native American and African-American communities, may mistrust scientists. Scientists, on the other hand, may not be aware of such feelings of mistrust when formulating research goals and planning tasks that require the involvement of these communities.[111] Also, the simple lack of experience in working with a particular organization or conducting community-based research can result in a considerable amount of time being spent to establish trust and define shared principles of collaboration.[108] Prior experience in working with partners and conducting transdisciplinary action–research eases these pressures considerably.[40]

Leadership and Member Characteristics

Leaders who are supportive, democratic, empowering, and committed and who encourage cooperation and engage the support of others significantly enhance transdisciplinary collaborations within both university and community settings.[29,107–109,113] Kumpfer and colleagues[113] conducted an exploratory study to test the relationship of leadership style to team effectiveness in an alcohol and drug abuse–prevention coalition. An empowering leadership style was found to boost member satisfaction and team efficacy, and was critical to the implementation and maintenance stages of the coalition as well as to its outcomes. Because coalitions are prone to internal disagreements, leaders adept at handling conflict are a valuable asset. By contrast, those who foster secrecy, in-group exclusiveness, and confrontation can weaken cooperative problem solving among members and minimize their use of intellectual resources. In inter-organizational and intersectoral coalitions, the presence of multiple program champions who are well-known and respected among partners can facilitate coordination across participating organizations.[109,112]

Members' readiness for collaboration also influences the outcomes of the community coalition. Collaboration-readiness factors include the sharing of a transdisciplinary ethic by coalition members and are expressed by their methodologic flexibility, cooperative spirit, inclusiveness, and positive attitudes toward collaboration.[107,109,114] In addition to their skills in research design and methods, members should be skilled in group processes, team development, negotiation, conflict resolution, and interpersonal communication.[107] Regular and unconstrained communication among team members—interpersonal as well as project-related—is a necessary condition to establish and maintain trust among members, provide clarity about coalition goals and member roles, and resolve disagreements or conflicts. The provision of well-developed electronic communication systems also facilitates coordination among partners.[29,109]

Organizational Support

A challenge faced by community coalitions is the decline in participation or involvement by members due

to circumstances such as lack of time, scarce resources, insufficient appreciation or recognition, competing institutional demands, loss of autonomy in decision making, frustration due to lack of progress, and interpersonal conflict.[107–109] Sustaining community coalitions requires that members' incentives to remain involved exceed the personal costs they incur through their participation. Examples of such incentives are financial compensation, training and educational opportunities, and peer recognition.[107] Broad-based institutional support for transdisciplinary collaboration (e.g., changes in tenure and promotion policies in universities) and rewards for community-based research (e.g., the publication of findings in respected journals) may increase the collaboration readiness of researchers and practitioners alike. Finally, assurances of long-term funding by public agencies and private foundations also enable coalition members to build sustainable partnerships.[29,107,108]

Studies of Transdisciplinary Science and Training Programs

Research on the antecedents, processes, and outcomes of scientific collaboration in transdisciplinary research centers and teams has grown steadily since the mid-1990s. Detailed reviews of these studies are available elsewhere.[10,11,13,22,25] The existing literature on the science of team science consists primarily of qualitative case studies employing structured interviews, surveys, and observations of collaborative activities among researchers as they occur in offices and laboratories. Very few experimental or quasi-experimental studies of transdisciplinary collaboration in scientific and training settings have been published (see Sonnewald[115] for an exception to this trend), thereby precluding the possibility of determining causal relationships among key variables. Nonetheless, systematic assessments of collaborative processes and outcomes gained through comparative case studies of transdisciplinary science and training centers have yielded valuable insights about the contextual factors that facilitate or constrain intellectual integration spanning multiple fields. In this section, some of the major themes that have emerged from earlier studies of team science are summarized.

Tendencies Toward Conflict

Conflict and tensions among members of a transdisciplinary center or team stemming from divergent disciplinary world views, competing theoretical and methodologic perspectives, different departmental affiliations, and dissimilar interpersonal styles hinder the formulation of clear goals and their accomplishment.[1,29,39,116] While disagreements and conflict can contribute to knowledge construction, learning, and innovation,[117] it is important to negotiate these differences, as they can foster interpersonal tensions, social fragmentation and subgrouping, and non-overlapping (even competing) agendas; eventually they can undermine the collaboration's ability to meet its goals.[26,29] Overcoming such conflicts requires that members of a collaboration establish familiarity with each other's way of thinking. This is possible through the prolonged and regular exchange of ideas and the development of informal personal relationships.[117] Off-site retreats have been shown to promote communication among team members, reduce interdisciplinary tension, and stimulate intellectual integration.[26] Having common visions and goals, a strong motivation to achieve them,[29,72] and the will to make the collaboration successful[117] also help members to put their disagreements behind them and move forward. The leadership skills of center directors, especially tactfulness in conflict resolution and the ability to encourage cooperation among members, emerge as an important asset for the success of transdisciplinary teams.[29,39]

Collaboration Readiness

Collaborative-readiness factors (the presence or absence of institutional supports for interdepartmental and cross-disciplinary collaboration; the breadth of disciplines, departments, and institutions included in a particular center; the degree to which team members have worked with each other on other projects; the spatial proximity of the members' offices or laboratories; and the availability of electronic linkages for efficient communication) strongly influence the team's prospects for success.[11,13,17,27,29,90,118] Previous case studies assessing collaborative outcomes in research centers and teams suggest that the more these contextual factors are present at the outset of the collaboration, the better a team's prospects for achieving its collaborative goals.[26,119]

Preparation and Practice

The importance of preparation and practice for ensuring successful collaboration has been emphasized in prior evaluations of transdisciplinary centers and teams.[14,26] Unrealistic expectations for complete cooperation and harmony, along with ambiguity of goals and intended outcomes, can impede the team's collaborative efforts. Members must be aware of the collaborative constraints, disagreements, and conflicts that they are likely to encounter over the course of the project and be prepared to dedicate considerable time and effort toward establishing common ground both intellectually and socially.[10,11,21,27,120] Thus, transdisciplinary collaboration, to be effective, requires substantial preparation, practice, and sustained effort.[29]

Conceptualizing the Ecology of Transdisciplinary Team Science and Collaborative Effectiveness

The review of empirical literature on team performance presented in the preceding sections highlights the importance of certain factors, identified across multiple research domains, that either enhance or hinder the effectiveness of transdisciplinary collaborations. For example, the crucial roles played by exemplary leaders of transdisciplinary initiatives, the importance of establishing interpersonal trust and respect among team members, and the organizational and technologic aspects of collaboration readiness are among the most-commonly-cited factors that exert strong influences on transdisciplinary collaborative processes and outcomes. An overview of the major factors that facilitate or constrain transdisciplinary collaboration, identified in each of the four research domains reviewed above, is presented in Table 1. The facilitating and constraining influences on transdisciplinary collaboration listed there and derived from earlier studies of team performance provide an empirical and conceptual foundation for understanding the ecology of team science and establishing a typology of contextual factors that jointly determine the effectiveness of transdisciplinary research and training initiatives.

Although the indicators of team performance in transdisciplinary collaborations vary (depending on the scientific and community problems being addressed; the scale of the collaboration [intra-organizational, inter-organizational, or intersectoral]; and center-specific goals and desired outcomes), certain structural features are nonetheless common to all transdisciplinary projects. First, transdisciplinary teams are inherently diverse in their composition, are charged with complex and difficult tasks, and can function in dynamic and uncertain social environments. Second, transdisciplinary collaborations are likely to be hybrid in nature, such that certain tasks requiring high structural interdependence and coordination are combined with others performed independently. Rewards in academic settings, on the other hand, traditionally have been based on individual merit. Scientists' contributions to a field are generally evaluated in terms of their single- or co-authored publications. Third, transdisciplinary science teams in academia are likely to have a higher degree of autonomy compared to those working in corporations. Finally, many transdisciplinary collaborations include members who are geographically dispersed.

Earlier studies reveal the difficulties that teams can encounter with the abovementioned circumstances. Heterogeneous and hybrid teams often experience interpersonal tensions and social fragmentation.[53,91] The ambiguity of goals, outcomes, and tasks makes transdisciplinary teams susceptible to conflict.[29] Uncertainty and instability—arising from changes in membership and administration, institutional policies, funding limitations, and time pressure—decrease the psychological safety of members and make the establishment and maintenance of trust among members particularly challenging. Moreover, the contexts in which teams work change with time. How can these barriers to teamwork in transdisciplinary collaborations be overcome or diminished, so that team members can reach their intellectual potential? In the ensuing sections are outlined the major intrapersonal, interpersonal, organizational, physical environmental, technologic, and political and societal factors that influence the effectiveness of team science, based on the literature review presented earlier. A summary of these key factors situated at each level of analysis (i.e., intrapersonal through political and societal) is provided in Table 2.

Intrapersonal Factors

Individuals who value collaboration, support a culture of sharing, and embrace a transdisciplinary ethic are well-suited for transdisciplinary teams.[13,39,109] Members' collaborative readiness (gauged in terms of their preparedness for the uncertainties and complexities of transdisciplinary teamwork,[29] their methodologic flexibility,[107] their openness to disparate disciplinary perspectives and world views, and their willingness to devote substantial amounts of time both to learning about others' expertise and developing intellectual and personal relationships) appears to be crucial to the success of team science initiatives. The sharing of egalitarian values,[39] allegiance to ethical conduct and shared responsibility,[121] and enthusiasm for achieving collaborative goals further enhance the prospects of transdisciplinary success. Other important considerations are the extent of collaborative experience that team members have had with each other in the past and their experience with transdisciplinary collaboration in general. A history of positive collaboration increases members' readiness for effective teamwork because they share more common ground at the outset and thus may not have to spend as much time establishing and sustaining trust (compared to teams whose members begin collaborating with little or no history of working together on earlier projects).[26,29,107,108,118,119]

In addition to team members' characteristics, a team leader's style plays a pivotal role in ensuring collaborative success. The most effective leaders in collaborative settings are empowering, inclusive, and transformational in their style; skillful in negotiating and resolving conflicts; and generous in offering constructive feedback and encouragement to colleagues. Those skills enable them to bolster trust and cohesiveness among team members and to facilitate high levels of performance.[29,52,107,113] Moreover, dynamic leadership—

Table 1. Factors facilitating or constraining collaborative effectiveness identified in four areas of team research

Area	Facilitating factors	Constraining factors
Social psychology and organizational behavior	Social cohesiveness and familiarity among team members Flexibility to adapt to changing task requirements and environmental conditions Transformational and empowering leaders who have excellent tactical skills and are able to foster collaboration through their respectful and inclusive orientation toward team members Participatory group goal setting and decision making, encouraging active roles to be played by all members in reaching consensus on major goals and decisions Team development strategies such as experiential learning and appreciative inquiry to encourage members' active participation Regular and effective communication and feedback among members to foster trust Organizational support for members' diversity and heterogeneity, especially in intellectual and scientific endeavors Opportunities for face-to-face contact and relationship building Access to physical environment resources that support collaboration (e.g., comfortable meeting areas, distraction-free and private work spaces for individualized and small-group tasks that require close concentration or confidentiality) Members share egalitarian values and mutual respect among team members throughout all stages of collaboration	Groupthink and social loafing, sometimes arising from prolonged familiarity and rigid operating procedures Inflexibility in the face of changing task demands and environmental conditions Lack of adequate and regular communication and feedback, resulting in low levels of trust among members and social fragmentation Leaders whose styles are noncollaborative and exclusionary rather than collaborative and inclusive Too-small or too-large team size in relation to specific task requirements and collaborative goals Hybrid task and reward structures in which tasks require interdependent efforts among members but incentives are distributed on an individualistic and meritocratic basis Insufficient opportunities for face-to-face contact among members Failure to identify and utilize the resources of all group members Work environments that inhibit communication among team members, hinder privacy regulation, or are too distracting Noncollaborative rather than collaborative attitudes and values among team members
Cyber-infrastructures for remote collaboration	Technologic infrastructure readiness, including availability of adequate bandwidth, connectivity, and electronic communications equipment to support remote collaboration Collaboration readiness of team members and organizations (i.e., their willingness to share information cooperatively; the existence of incentives to participate in and sustain collaboration; and broad-based institutional, organizational, and administrative support) Technology readiness of users (i.e., their adaptation to habits and patterns of technology use such as familiarity with tools, making information accessible to others, providing regular and prompt feedback, and adequate preparation for meetings) Ample opportunities for face-to-face contact throughout all stages of remote collaboration Regular face-to-face meetings and socialization among remote team members to increase trust and to create and sustain group identity Sustained communication among members to establish common ground and reduce task-related uncertainties Enthusiastic leaders strongly committed to effective remote collaboration Creation of new roles and communication patterns that enhance distance collaboration	Lack of adequate technical infrastructure such as networking, bandwidth, technical support, and appropriate hardware and software Technologic concerns about speed, data security, integrity, privacy, and effective access and retrieval that render distance collaboration complex and challenging Constrained audio and visual choices and the use of media that are inappropriate for the task at hand Financial costs and expenditures of time and effort for establishing requisite infrastructure for distance collaboration Lack of experience and familiarity with the use of distance-collaboration tools Communication challenges in establishing team identity and trust due to the absence of shared physical settings along with nonverbal and spatial cues Absence of a culture of sharing information and non-alignment of reward structures to encourage collaboration and the use of collaboration tools

(continued on next page)

Table 1. Factors facilitating or constraining collaborative effectiveness identified in four areas of team research *(continued)*

Area	Facilitating factors	Constraining factors
Community coalitions among scientists and practitioners	Identification of common and clear goals, objectives, outcomes, and consensus among team members regarding their collaborative priorities Development of a shared statement of principles among coalition members and formalization of mutual benefits and responsibilities Continuity of collaboration throughout all phases of the coalition Joint development of operating norms that encourage open communication, inclusiveness, and shared decision making Prior positive experiences of collaboration with participating community organizations and their members Supportive, democratic, and empowering leaders who engage the participation of all members, encourage their cooperation, and are skilled in conflict resolution Members' readiness for collaboration, including their cooperative orientation, methodologic flexibility, positive attitudes toward collaboration, and interpersonal communications skills and training Presence of well-developed electronic communication systems to encourage and sustain collaboration among team members Strong incentives to participate and remain involved (e.g., financial, training and education, public recognition, tenure and promotion) Sustained support by funding agencies to enable the coalition to accomplish its major goals	Disagreement and conflicts due to divergent understandings of the coalition's goals and timelines among community practitioners and academic researchers Presence of unclear, ambiguous, and complex goals Conflicts arising from different scientific world views, disciplinary perspectives, and decision-making styles Inequitable distribution of decision-making power, information, time, resources, and control over the coalition's action–research activities Perception of status differences between scientists and community practitioners Lack of trust and respect arising from negative experiences in prior collaborative projects Leaders who encourage secrecy, in-group exclusiveness, and interpersonal competition and confrontation Absence of adequate and regular communication among members Decline of members' participation, involvement, or both, in coalition activities due to lack of time, personal costs, absence of strong incentives to participate, and competing institutional demands Uncertainties about and absence of sustained funding to support the coalition's long-term goals and activities
Evaluative studies of transdisciplinary research centers and training programs	Prior experience of positive collaboration with team members on earlier transdisciplinary projects Presence of a strong, shared vision; agreement on highest-priority goals and the timelines for achieving them Exemplary leadership skills of center directors, especially conflict-resolution skills and ability to encourage cooperation among members while easing tensions among divergent scientific world views and disciplinary perspectives Prolonged and regular exchange of ideas to encourage the development of positive and informal interpersonal relationships Presence of electronic systems (e.g., intranet and Internet sites) to facilitate regular communication among center members Spatial proximity of scientists' offices and laboratories Physical environments that afford opportunities for face-to-face contact among center members (e.g., comfortable, shared-meeting areas; distraction-free office and laboratory settings) Members' awareness of and preparation for the collaborative constraints, disagreements, and conflicts they are likely to encounter over the course of their collaboration; availability of training resources and negotiation strategies for resolving the tensions inherent in transdisciplinary research and training initiatives	Lack of experience among team members in working together on prior transdisciplinary research and training programs Lack of a shared vision among members about highest-priority goals and the timelines for achieving them Conflicts and tensions stemming from alternative disciplinary perspectives, multiple departmental affiliations, and contrasting interpersonal styles Lack of collaborative skills and management experience among available leaders Lack of both regular communication among team members and adequate cyber-infrastructure to support frequent and effective exchanges of information Absence of institutional supports and organizational incentives to sustain interdepartmental and inter-university collaboration Lack of physical environments (e.g., shared team-space) that encourage face-to-face contact among members of transdisciplinary research centers and training programs Lack of training programs to enhance team members' readiness for collaboration in transdisciplinary research and training activities; unrealistic expectations for complete cooperation and harmony among team members

Table 2. Key contextual factors that influence transdisciplinary team effectiveness at each level of analysis

Intrapersonal	Interpersonal	Organizational/institutional	Physical/environmental	Technologic	Sociopolitical
Members' attitudes and values during the formation of a transdisciplinary collaboration, such as valuing collaboration, supporting a culture of sharing, embracing a transdisciplinary ethic, and sharing egalitarian values Members' collaborative readiness in terms of their openness to other disciplinary perspectives; willingness to devote large amounts time and effort to building personal relationships; and preparedness for the uncertainties, tensions, and complexities inherent in transdisciplinary teamwork Members' collaborative experiences with each other on earlier projects Presence of exemplary leaders who are empowering, inclusive, and transformational; a participatory leadership style that enables all members to play an active role in team goal-setting and decision-making activities	Regular and effective social and intellectual communications to establish common ground, overcome task-related uncertainties, and develop consensus around a shared vision and collective goals Diversity of members' knowledge and skills Members' ability to learn about each other's expertise and create a hospitable conversational space Mutual respect among team members Members' familiarity and social cohesiveness, coupled with their ability to adapt flexibly to changing circumstances, remain open to new perspectives, and challenge existing assumptions and procedures	Presence of strong organizational incentives to encourage participation and sustain collaborative orientation among members Broad-based institutional support for intradepartmental and inter-university collaboration through modifications of organizational structures and administrative routines (e.g., merit and promotion procedures in academic settings) Nonhierarchic arrangements that provide autonomy to team members and encourage participatory goal setting and decision making Breadth of disciplinary perspectives represented among team members Scheduling of retreats and informal social events to encourage informal contact and communication among members Assurances of long-term support by funding agencies so that teams have more time to establish trust, build relationships, and accomplish their goals	Spatial proximity of team members' offices and laboratories to encourage informal contact and communication Availability of comfortable meeting areas for group discussion and brainstorming activities Access to distraction-free work spaces for individualized tasks requiring concentration, confidentiality, or both Physical environments that support members' efforts to regulate their interpersonal privacy and accessibility to others over the course of their collaboration	An organization's technologic infrastructure readiness, or access to necessary bandwidth, electronic networking capabilities, linkages between sites, and technical support for remote collaboration Provisions for high-level data security, integrity, privacy, rapid retrieval, and long-term archival access, and technologies that facilitate the formation of knowledge and social networks Members' technologic readiness, including their knowledge of and familiarity with various electronic information and communication tools, protocols, codes of conduct for distance collaboration, and the effectiveness of their communication styles	Easing of international tensions through cooperative policies that encourage exchanges of scientific information and transdisciplinary collaboration among scientists from different regions of the world Enacting policies and protocols to support effective transdisciplinary collaboration, such as those ensuring ethical scientific conduct and management of intellectual property ownership and licensing Occurrences of adverse global environmental changes and public health problems that prompt intersectoral and international transdisciplinary collaboration in scientific research and training programs

whereby members share authority and responsibility according to the shifting requirements of their tasks—lessens the pressures felt by single individuals while enabling all members to play an active role in team decision making and activities.[61]

Interpersonal Factors

Interpersonal communication has been found in earlier studies[1,13,26] to be a critical determinant of collaborative effectiveness. Because of the inherent diversity of transdisciplinary teams, regular and effective intellectual and social communications are necessary so members can clarify roles, task requirements, collective goals, and intended outcomes as well as learn about their colleagues, understand and respect their alternative perspectives, and eventually transcend disciplinary and departmental boundaries to develop novel conceptual frameworks for understanding and solving the problems under investigation. If members are to learn from each other as the team develops, build a shared identity and a hospitable conversational space, strengthen collaborative processes, and ease interdisciplinary tensions, they must be able to engage in ongoing, mutually respectful, and constructive communication. Such communication, by enabling them to develop a shared vision and articulate common goals and by encouraging positive imagery and appreciative inquiry, empowers them to surpass obstacles and achieve those goals.[85] Furthermore, it is important that members be able to adapt to changing circumstances and remain open to new perspectives, particularly as the team matures and becomes more cohesive. The capacity of team members to adapt to new situations and challenge their existing assumptions and procedures is a crucial ingredient of collaborative success.[60,63,64]

Organizational and Institutional Factors

A prerequisite for sustaining motivation among participants in team science initiatives is the presence of strong organizational incentives.[107,109] For instance, an important incentive for motivating junior researchers to participate actively in transdisciplinary research and training initiatives is greater recognition for collaborative work through changes in university tenure and promotion policies.[23,24] Institutional support for intradepartmental and inter-university collaboration can be increased through the modification of organizational structures and routines.[17] Nonhierarchic organizations that encourage participatory goal setting and decision making foster inclusiveness and more-effective collaboration. Assurances of long-term funding by public agencies and private foundations also provide team members more time to develop the relationships and trust so critical for collaborative success.

An organization's collaboration readiness—reflected in the extent of its collaborative activities, breadth of disciplines, culture of sharing information, equitable access to information and technology, preparation for meetings, and ample opportunities for brainstorming new ideas—contributes in important ways to effective collaboration.[29,90] Because team science projects require substantial time expenditure for group meetings and brainstorming sessions, participating organizations must recognize and reward members for engaging in collaborative activities by providing organizational, environmental, and technologic support and incentive structures.

Physical Environmental Factors

One strategy for encouraging communication, trust, and the integration of intellectual ideas is to maximize spatial proximity among members' offices and laboratories.[29] Where this arrangement is not feasible, it becomes important to schedule regular face-to-face meetings, social gatherings, retreats, and other opportunities for team members to meet and communicate. Earlier studies[29] also indicate that reduced spatial, temporal, and emotional cues in remote collaborations render interpersonal trust fragile, and are often associated with misunderstandings, conflict, and social fragmentation. Face-to-face contact prior to engaging in remote collaboration is essential in establishing some degree of trust at the outset of the project.[90] At the same time, earlier studies[69–71] of team environments suggest the importance of providing environmental support (e.g., access to distraction-free work spaces and comfortable meeting areas) to facilitate members' regulation of interpersonal privacy and their participation in both individualized tasks requiring high levels of concentration or confidentiality and collective activities involving group discussion and brainstorming.

Technologic Factors

Technologic readiness and technologic infrastructure readiness[90] strongly influence remote as well as place-based collaborations. The organization's technologic infrastructure readiness—access to necessary bandwidth, electronic-networking capabilities, linkages between sites, and technical support—is a vital component of successful transdisciplinary collaborations.[90] Providing data security, integrity, privacy, rapid retrieval, long-term archival access, and technologies that facilitate the formation of knowledge and social networks has been found to enhance remote scientific collaborations.[46,72] Members' technologic readiness, including their familiarity with various electronic information and communication tools, protocols, and codes

of conduct as well as the effectiveness of their communication style, is directly related to the team's prospects for achieving its scientific goals through remote transdisciplinary collaboration.[90]

Political and Societal Factors

The easing of political barriers through cooperative international policies and the reduction of tensions between nations can encourage the initiation and longer-term success of transdisciplinary science collaborations.[28,122,123] At the same time, global environmental changes and health challenges have spawned large-scale international collaborations for scientific research and community health promotion, exemplified by the WHO's Healthy Cities Program.[124–126] At state and national policymaking levels, the enactment of protocols for ensuring ethical scientific conduct, adjudicating claims to intellectual property ownership and licensing, and protecting animal and human subjects' rights provide the legal foundations for conducting effective large-scale transdisciplinary collaborations.[72,127]

A diagrammatic representation of these broad categories of contextual influences on transdisciplinary research and training programs is provided in Figure 1. The multiple categories of contextual factors shown there provide a typology of key variables that influence the effectiveness of transdisciplinary collaborations, grouped according to the intrapersonal, interpersonal, organizational, institutional, physical environmental, technologic, and political and societal levels of analysis discussed above.

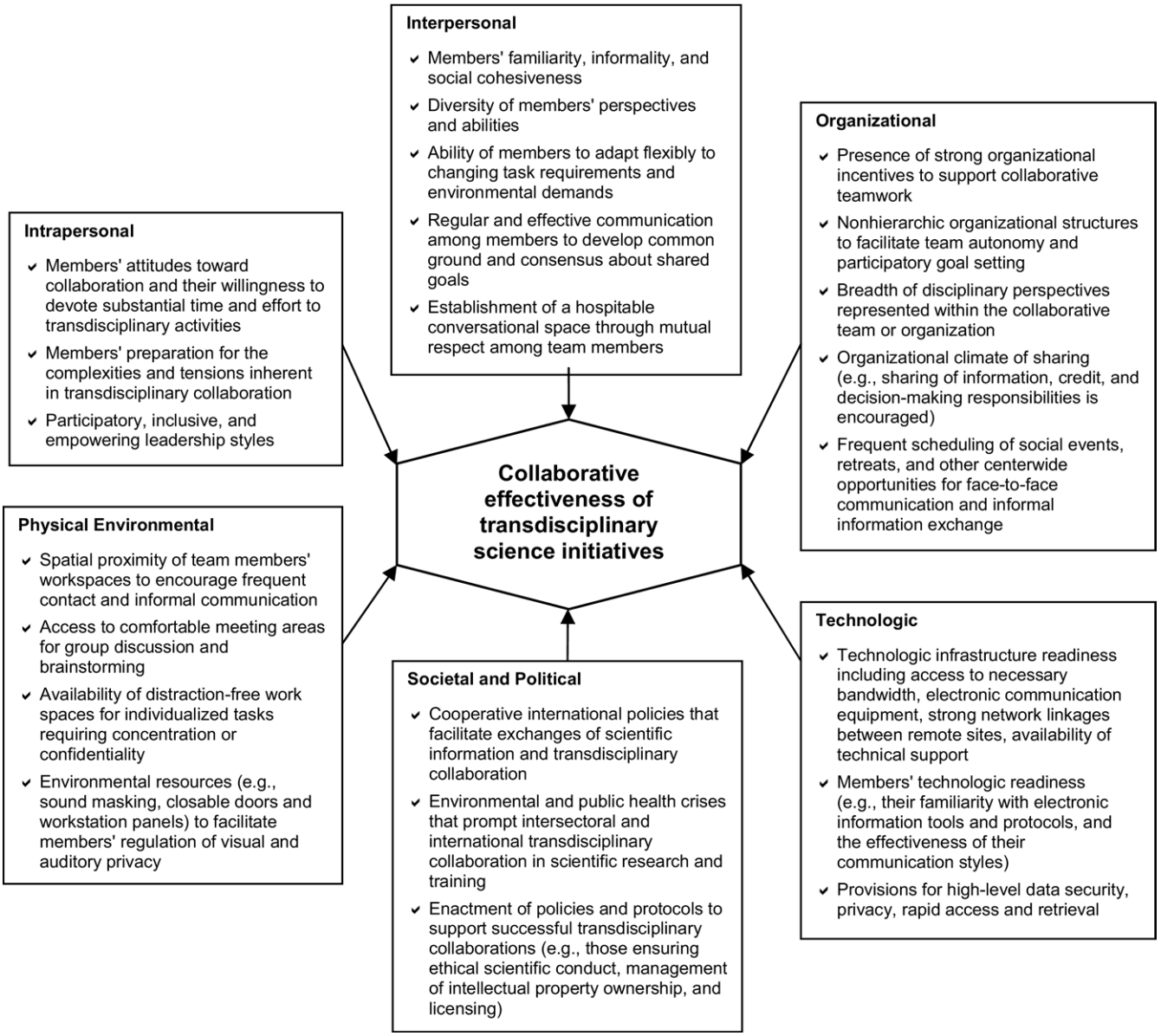

Figure 1. Typology of contextual factors influencing transdisciplinary scientific collaboration

Designing and Managing the Ecology of Team Science to Enhance Collaborative Effectiveness in Transdisciplinary Research and Training

This concluding section focuses on an important issue raised at the outset of the article—namely, the need to better understand the contextual determinants of collaborative success as a basis for making future investments in large-scale team science initiatives more strategic (i.e., scientifically productive and financially cost effective). Having reviewed the empirical evidence for contextual determinants of team performance across four distinct areas of research, this study addresses below the practical implications of that evidence for future efforts to enhance the success of transdisciplinary science initiatives.

The sheer diversity of transdisciplinary research and training programs (reflected in their different structural features, stated goals, and effectiveness criteria) suggests that the contextual factors most crucial for collaborative success will vary from one initiative to another. For example, having an adequate technologic infrastructure in place at remote sites is an essential prerequisite for effective distance collaboration but may not be as crucial for the members of a transdisciplinary team who work together at the same location.[46,90] Similarly, community-based program champions and multiple leaders representing different organizations enhance the effectiveness of inter-organizational and intersectoral transdisciplinary coalitions, but may not be necessary for the success of transdisciplinary research centers linked primarily to academic institutions.[112] Thus, there is no one-size-fits-all set of contextual factors that can be expected to exert the same degree of influence on collaborative outcomes for all research teams and settings; nor are precise algorithms available for gauging the relative contributions of multiple contextual variables (e.g., those listed under each level of analysis shown in Figure 1) to collaborative success. For any given initiative, at least some of the important determinants of effective collaboration are likely to be specific to the type of transdisciplinary project or program undertaken (e.g., single versus multiple organizations and locations, large versus small numbers of participants and disciplinary perspectives).

At the same time, this review of the scientific literature on team performance identified certain intrapersonal and situational variables (e.g., empowering-leadership styles, the regularity and effectiveness of team communication, opportunities for informal face-to-face contact, members' readiness and preparation for transdisciplinary collaboration) that emerged across multiple research domains as important contributors to collaborative success within a broad array of transdisciplinary projects and programs (e.g., university-based research teams, community coalitions for health promotion, intersectoral partnerships for policy change). Moreover, these factors may act synergistically in some collaborative settings to influence team processes and outcomes in an interactive or cumulative fashion.[29,112]

What are the implications of these findings for designing and managing effective team science initiatives? Generally speaking, the evidence on team performance suggests the value of optimizing as many factors as possible that have been found to facilitate collaborative success (i.e., those listed in Tables 1 and 2) whenever a new team science initiative is developed and implemented. The research literature also suggests, however, that not all of the conditions listed under each analytic level of the proposed typology (Figure 1) must be present in all instances to ensure that a particular initiative is effective. Furthermore, efforts to optimize an unlimited array of contextual resources for all team science initiatives would be neither feasible nor justifiable in terms of cost-effectiveness criteria, especially considering the recent criticisms of team science and concerns about budgetary appropriations for transdisciplinary research programs versus single-investigator grants.[18,19] Thus, a more compelling strategy for developing and managing team science initiatives is to match the particular goals and structure of a transdisciplinary research program with targeted investments in those contextual resources (e.g., collaboration-readiness factors) that are specific to the project at hand and are most likely to be essential for its success.

Accordingly, it is useful to distinguish between the contextual determinants of collaborative success that are highly specific to the requirements of a given initiative and other, more broadly influential factors whose effects extend across a wider array of transdisciplinary research settings and programs. Before a team science initiative is launched, efforts should be made to ensure that, at a minimum, project-specific requirements for collaborative success are present at the outset (e.g., access to the requisite electronic infrastructure among team members who must coordinate their efforts across remote sites). To the extent that additional investments can be made to ensure that other generally influential conditions for success are present (e.g., leaders who have extensive experience in managing distance collaboration, frequent face-to-face meetings among team members over the course of a multisite collaboration), they should be undertaken to further improve the prospects for collaborative success.

When deciding how to allocate program-development funds (either to project-specific requirements alone or to a larger set of collaboration-readiness factors that include both project-specific and more generally influential determinants of success), it is important to consider the degree of complexity inherent in the proposed transdisciplinary science initiatives. Transdisciplinary science projects and programs can be arrayed along a continuum of complexity, ranging from simple to highly complex.

Key determinants of the complexity of transdisciplinary initiatives include: (1) the number of scientists participating in the initiative (e.g., a solo investigator working at the interface of two or more fields, a group of 2–3 scientists working at the same site, or 15–30 scientists collaborating across multiple organizations and geographic locations); (2) the diversity of disciplinary perspectives and scientific world views represented among participants, ranging from relatively similar to widely divergent; (3) the anticipated duration of the project or program (e.g., a 1–2 year project compared to a 5–10-year research and training initiative); (4) whether participants are working to accomplish a small or large number of programmatic goals (e.g., scientific discovery and integration, the effective training of new transdisciplinary scientists, translations of scientific findings into community health programs and policy initiatives, the improvement of population health outcomes); and (5) the organizational, analytic, and geographic scope of an initiative, reflected in the number of organizations, levels of analysis, and geographic sites incorporated within a particular program.

Earlier studies of transdisciplinary collaboration suggest that the more complex a transdisciplinary science initiative is, the larger the number of both project-specific and general collaboration-readiness factors required to ensure its success. For instance, many, if not most, of the contextual influences on collaborative effectiveness identified in earlier social psychological and organizational behavior studies (e.g., exemplary leadership styles, electronic communications infrastructure, training programs to prepare participants for the tensions inherent in transdisciplinary teamwork) should be less important to the success of individual scientists or very small teams of researchers working at the same site than the success of larger and more-diverse teams that are attempting to collaborate across multiple locations and establish translational partnerships with health practitioners and non-academic organizations in the local community. Similarly, to the degree that a transdisciplinary initiative has established a large number of diverse goals spanning scientific, training, policy, and public health outcomes, the contextual circumstances required to facilitate the attainment of those goals and the criteria for evaluating the team's effectiveness in meeting them become more varied and complex (*vis-à-vis* initiatives whose major collaborative goals are more narrowly targeted).

In sum, the preceding review of the research on team performance suggests that investments in team science initiatives should be allocated strategically prior to initiating new transdisciplinary research and training programs and be tailored to match the complexity of their goals and organizational structure. To accomplish this matching, it is important that project-specific audits be conducted to ascertain which of the contextual factors outlined in Table 2 and Figure 1 should receive the greatest priority and investment of resources prior to the launch of a new transdisciplinary program. Especially for more-complex transdisciplinary science and training initiatives that include large numbers of participants, encompass diverse goals, and span multiple organizations and sites, leaders should be chosen carefully to include individuals who have prior experience managing large-scale transdisciplinary programs and interpersonal styles that promote effective collaboration. Furthermore, new training programs for participants in large-scale team science initiatives should be developed to better prepare them for the challenges and complexities that often arise in transdisciplinary collaborations.[128] Finally, grant funding to support the establishment of long-term transdisciplinary research centers and programs should be targeted not only to prospective applicant teams that have demonstrated high levels of collaboration readiness prior to their initiation of the proposed project, but also to relatively less-experienced teams that show great scientific promise and whose collaborative success may be accelerated by targeted investments of funding aimed at increasing their readiness and resources for collaboration (e.g., the provision of shared research space, electronic infrastructure, or transdisciplinary training modules).

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