The Science of Team Science

Overview of the Field and Introduction to the Supplement

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Abstract: The science of team science encompasses an amalgam of conceptual and methodologic strategies aimed at understanding and enhancing the outcomes of large-scale collaborative research and training programs. This field has emerged rapidly in recent years, largely in response to growing concerns about the cost effectiveness of public- and private-sector investments in team-based science and training initiatives. The distinctive boundaries and substantive concerns of this field, however, have remained difficult to discern. An important challenge for the field is to characterize the science of team science more clearly in terms of its major theoretical, methodologic, and translational concerns. The articles in this supplement address this challenge, especially in the context of designing, implementing, and evaluating cross-disciplinary research initiatives. This introductory article summarizes the major goals and organizing themes of the supplement, draws links between the constituent articles, and identifies new areas of study within the science of team science.
(Am J Prev Med 2008;35(2S):S77–S89) © 2008 American Journal of Preventive Medicine

Background

The past two decades have witnessed a surge of interest and investments in large-scale team science programs.[1–7] Ambitious multiyear initiatives to promote cross-disciplinary collaboration in research and training have been launched by several public agencies and private foundations.[8–15] Considering the enormous complexity and multifactorial causation of the most vexing social, environmental, and public health problems (e.g., terrorism and interethnic violence; global warming; cancer, heart disease, diabetes, and AIDS; health disparities among minority populations), efforts to foster greater collaboration among scientists trained in different fields are not only a useful but also an essential strategy for ameliorating these problems.[16–22] At the same time, some observers of science policy question whether the current popularity of cross-disciplinary research and training is merely a passing fad whose scientific and societal value, relative to smaller-scale unidisciplinary projects, has been overstated.[23] Critics of cross-disciplinary initiatives contend that they divert valuable resources from important discipline-based research and draw scientists into collaborative centers and teams who otherwise might be more productive working independently or as co-investigators on smaller-scale projects.[24,25]

As public and private investments in team science initiatives have grown and debates about their intellectual and societal value have ensued, the importance of clearly defining and evaluating the effectiveness of these programs has become more evident.[26–31] Practical concerns about gauging the value added and the return on investment accruing from large research initiatives[4,26,32] have given rise to **the science of team science**, a rapidly emerging yet still-amorphous field characterized by a lack of consensus about its defining substantive boundaries and core concerns.

The goals of this article are twofold: (1) to describe the science of team science in terms of its major conceptual, methodologic, and translational concerns; and (2) to introduce the present supplement to the *American Journal of Preventive Medicine* on the science of team science by offering an overview of its organization and specific aims.[9,19,27,33–49]

The Science of Team Science: Units of Analysis and Distinguishing Features

It is important to distinguish between team science initiatives themselves and the science-of-team-science field, whose principal units of analysis are the large research and training initiatives implemented by public agencies and nonpublic organizations and the various projects within each initiative conducted by scholars who work within and across their respective fields. Team science initiatives are designed to promote collaborative—and often cross-disciplinary—approaches to analyzing re-

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doi:10.1016/j.amepre.2008.05.002

search questions about particular phenomena (e.g., the joint influence of social, behavioral, and biogenetic factors on cancer etiology and treatment examined by Hiatt and Breen,[19] and the multilevel determinants of health disparities discussed by Holmes et al.[34] in this supplement). The science-of-team-science field, on the other hand, is a branch of science studies concerned especially with understanding and managing circumstances that facilitate or hinder the effectiveness of team science initiatives.[50–54] The field as a whole focuses not on the phenomena addressed by particular team science initiatives (e.g., cancer, heart disease, obesity, community violence, environmental degradation), but rather on understanding and enhancing the antecedent conditions, collaborative processes, and outcomes associated with team science initiatives more generally, including their scientific discoveries, educational outcomes, and translations of research findings into new clinical practices and public policies.[9,35,55] Some of the distinguishing features of team science initiatives and the unique substantive concerns of the science-of-team-science field are outlined below.

Characteristics of Scientific Initiatives and Teams

Efforts to integrate knowledge in the science-of-team-science field face considerable challenges, owing to the highly disparate units of analysis found in the earlier studies of scientific teams.[27,36,56] Research teams, for example, may consist of investigators drawn from either the same or different fields (i.e., unidisciplinary versus cross-disciplinary teams). These teams vary not only in terms of their disciplinary composition but also in terms of their size, organizational complexity, and geographic scope, ranging from a few participants working at the same site to scores of investigators dispersed across multiple geographic and organizational venues.[55,57] Furthermore, the goals of team science initiatives are quite diverse (e.g., spanning scientific discovery; training; and clinical, translational, public health, and policy-related goals), and both the quality and level of intellectual integration intended and achieved among disciplines varies from one program to the next (i.e., along a continuum ranging from unidisciplinary to multidisciplinary, interdisciplinary, and transdisciplinary integration, as described more fully below).[27,37,58–60]

Because team science initiatives differ along so many dimensions, including their size, goals, duration, organizational structure, and cross-disciplinary scope, it is important to be clear at the outset about the kinds of research and training initiatives emphasized in the present discussion. Team-based projects can include a handful of scientists working together at a single site, but the focus here is on the larger and more-complex initiatives comprising many (e.g., often between 50 and 200) investigators who work collaboratively on multiple, closely related research projects, and who may be dispersed across different departments, institutions, and geographic locations.[55] Trochim and colleagues,[6] for example, define large research initiatives as grant-funded projects solicited through specific requests for applications with an average annual expenditure of at least $5 million. The usual duration of these initiatives (e.g., NIH P50 and U54 Centers, National Cancer Institute [NCI] Specialized Programs of Research Excellence [SPOREs]) is 5 years, and they may be refunded, thus extending over one or more decades, in some cases.[61] Some especially broad-gauged initiatives, such as the NIH Roadmap and the Office of Portfolio Analysis and Strategic Initiatives (OPASI) programs, provide the organizational framework and funding source for scores of other interrelated research and training initiatives, all of which are designed to promote cross-disciplinary scientific collaboration.[11,14] Often, large research initiatives incorporate career development and training components as well as clinical translation, health promotion, and policy-related functions.[13,62–64] The articles in this supplement address the full range of scientific, training, clinical translation, community outreach, health promotion, and public-policy goals emphasized within relatively large team science initiatives of varying size and complexity.

Large initiatives also vary with respect to the collaborative orientations and disciplinary perspectives of team members. This discussion focuses on initiatives intended to promote **cross-disciplinary** rather than **unidisciplinary** collaboration.[a] Cross-disciplinary teams strive to combine and, in some cases, to integrate concepts, methods, and theories drawn from two or more fields. Three different approaches to cross-disciplinary collaboration have been described by Rosenfield.[60] **Multidisciplinarity** is a process in which scholars from disparate fields work independently or sequentially, periodically coming together to share their individual perspectives for purposes of achieving broader-gauged analyses of common research problems. Participants in multidisciplinary teams remain firmly anchored in the concepts and methods of their respective fields. **Interdisciplinarity** is a more robust approach to scientific integration in the sense that team members not only combine or juxtapose concepts and

[a]Distinctions between cross-disciplinary and unidisciplinary collaboration depend on how individual disciplines are defined and bounded.[65] Disciplines are generally organized around distinctive substantive concerns (e.g., biological, psychological, environmental, or sociologic phenomena); analytic levels (e.g., molecular, cellular, cognitive, behavioral, interpersonal, organizational, community); and concepts, methods, and measures associated with particular fields. The boundaries between disciplines and subdisciplines are to some extent arbitrarily defined and agreed upon by communities of scholars.[66,67] For instance, the boundaries between some fields may be overlapping (e.g., physiology and molecular biology) and other fields, such as public health and urban planning, are inherently multidisciplinary in that they combine several disciplinary perspectives in analyses of population health and urban development.

Table 1. Definitions and examples of scientific orientations[60]

Scientific orientation	Definition	Example
Unidisciplinarity	**Unidisciplinarity** is a process in which researchers from a **single discipline** work together to address a common research problem.	A team of pharmacologists collaborate on a laboratory study of the relationships between nicotine consumption and insulin metabolism.
Multidisciplinarity	**Multidisciplinarity** is a **sequential** process whereby researchers in different disciplines work **independently**, each from his or her own discipline-specific perspective, with a goal of eventually combining efforts to address a common research problem.	A pharmacologist, health psychologist, and neuroscientist each contribute sections to a multi-authored manuscript that reviews research in their respective fields pertaining to the links between nicotine consumption, changes in brain chemistry and caloric intake induced by nicotine, and physical activity levels.
Interdisciplinarity	**Interdisciplinarity** is an **interactive** process in which researchers work **jointly**, each drawing from his or her own discipline-specific perspective, to address a common research problem.	A pharmacologist, health psychologist, and neuroscientist conduct a collaborative study to examine the interrelations among patterns of nicotine consumption, brain chemistry, caloric intake, and physical activity levels. Their research design incorporates conceptual and methodologic approaches drawn from each of their respective fields.
Transdisciplinarity	**Transdisciplinarity** is an **integrative** process in which researchers work jointly to develop and use a shared conceptual framework that **synthesizes** and **extends** discipline-specific theories, concepts, methods, or all three to create **new** models and language to address a common research problem.	A pharmacologist, health psychologist, and neuroscientist conduct a collaborative study to examine the interrelations among nicotine consumption, brain chemistry, caloric intake, and physical activity levels. Based on their findings, they develop a neurobehavioral model of the links among tobacco consumption, brain chemistry, insulin metabolism, physical activity, and obesity that integrates and extends the concepts and methods drawn from their respective fields.

methods drawn from their different fields, but also work more intensively to integrate their divergent perspectives, even while remaining anchored in their own respective fields.[27]

Transdisciplinarity is a process in which team members representing different fields work together over extended periods to develop shared conceptual and methodologic frameworks that not only integrate but also transcend their respective disciplinary perspectives.[b] Examples of unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary scientific orientations are provided in Table 1. Transdisciplinary collaborations perhaps have the greatest potential to produce highly novel and generative scientific outcomes, but they are more difficult to achieve and sustain than unidisciplinary, multidisciplinary, and interdisciplinary projects due to their greater complexity and loftier aspirations for achieving transcendent, supra-disciplinary integrations.[27,31,37,56,68–70]

The ensuing discussion focuses primarily on interdisciplinary and transdisciplinary science initiatives in which an explicit goal of the collaboration is to integrate theories, methods, and training strategies drawn from two or more fields. Examples of large-scale interdisciplinary and transdisciplinary team initiatives are the NCI, National Institute of Drug Abuse (NIDA), and National Institute on Alcohol Abuse and Alcoholism (NIAAA) Transdisciplinary Tobacco Use Research Centers (TTURCs)[71]; the NCI Transdisciplinary Research on Energetics and Cancer (TREC) Centers[72]; the Centers for Excellence in Cancer Communications Research (CECCR)[73]; the National Institute of Environmental Health Sciences (NIEHS)[64]; the National Institute on Aging (NIA)[64]; the NIH Office of Behavioral and Social Sciences Research (OBSSR)[64]; the NCI Centers for Population Health and Health Disparities (CPHHD)[64]; and the National Center for Research Resources (NCCR) Clinical and Translational Science Centers (CTSC).[13,74]

The distinctions among unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary forms of scientific collaboration are directly relevant to the development of criteria for gauging the success of team science initiatives. In particular, measures of scientific collaboration and its outcomes should be appropriately matched to the research, training, and translational goals of particular initiatives. A key goal of interdisciplinary and transdisciplinary initiatives, for example, is

[b]As Klein[27] has observed, cross-disciplinary teams, rather than being exclusively multidisciplinary, interdisciplinary, or transdisciplinary in their orientation, often incorporate a mixture of these approaches, each of which may become more or less predominant during different phases of collaboration.

to bridge the perspectives of different fields through the collaborative development of integrative conceptualizations, methodologic approaches, and training strategies. Thus, an important criterion for gauging the success of these initiatives is the extent to which cross-disciplinary integrations are actually achieved by research teams.[27,37,75] These issues are discussed more fully below.

Substantive Concerns and Research Foci Within the Science-of-Team-Science Field

The science-of-team-science field encompasses an amalgam of conceptual frameworks and methodologies that have been used in earlier studies to assess the processes and outcomes of cross-disciplinary research centers and teams. The findings from these studies are part of a rapidly growing database within the science-of-team-science field.[2,3,8,10,31,32,38,74–80] Common themes that offer a basis for integrating prior and future studies of team science initiatives are beginning to emerge, but the field still lacks the conceptual coherence of a more established and widely recognized scientific paradigm.[27,39,66] Greater scientific coherence may be achieved as science-of-team-science scholars reach further agreement about the field's major conceptual, methodologic, and translational concerns. Several substantive concerns and challenges within the science-of-team-science field are outlined below.

Conceptual Concerns

Scholars in the science-of-team-science field have given considerable attention to at least two broad categories of conceptual tasks: (1) defining key terminology and (2) developing theoretical models to account for the circumstances under which team science initiatives are more or less effective.

Defining key terms. It is important to clearly define the major units of analysis and the core subject matter of the science-of-team-science field (e.g., organizational complexity and geographic scope of team science initiatives; different forms of cross-disciplinary research, including multidisciplinary, interdisciplinary, and transdisciplinary collaboration).[8,58] A major challenge is to specify the dimensions of program effectiveness or success as they pertain to team science initiatives. For instance, the quality of scientific work may be defined differently in the context of interdisciplinary and transdisciplinary team initiatives than in unidisciplinary projects. Traditional criteria of scientific quality include conceptual originality; methodologic rigor (e.g., validity and reliability of empirical findings); and the quantity of research outputs produced, such as peer-reviewed publications. In the context of team science initiatives, however, the quality and scope of interdisciplinary and transdisciplinary integration (e.g., the development of integrative conceptualizations and methodologic approaches, the development of training programs bridging two or more fields, the emergence of new hybrid fields of inquiry) are important facets of collaborative scholarship that must be considered in view of their explicit mission to promote scientific integration.[14,27,31,37]

Also, because the scientific, educational, and translational aims of team science initiatives are highly diverse, it is crucial to identify the highest-priority goals and corresponding criteria of success for any given program.[27,36] The overall success of large-scale initiatives (e.g., the NCI TTURC, CECCR, TREC, and CPHHD programs) may be construed differently than the effectiveness of the particular research centers and projects subsumed within them.[9,78] For instance, the cumulative scientific and public health advances associated with large-scale initiatives are qualitatively distinct from the more circumscribed intellectual achievements of a particular research center or team. For both broad-gauged initiatives and their subsidiary projects, key dimensions of program effectiveness (e.g., development of transdisciplinary syntheses, publication of empirical findings, translations of research into clinical practices and policy innovations) are likely to shift as team members progress through the initial, intermediate, and later stages of collaboration.[6,31,36] Collaborative processes and outcomes appear to be stage-dependent, and therefore should be defined differently for near-, mid-, and longer-term phases of team science programs.

Finally, for many team science initiatives, it is important to define not only the distinguishing features of effective scientific collaboration but also the essential facets of successful interdisciplinary and transdisciplinary training (e.g., the career trajectories and intellectual contributions of current and former trainees).[37,62,81–83]

Developing theoretical models and conceptual frameworks. To date, a number of conceptual models have been proposed by science-of-team-science scholars to identify key antecedent conditions, intervening processes, and outcomes associated with team science initiatives and to explain the interrelationships among them (e.g., the presence of institutional supports or constraints at the beginning of an initiative and their impact on subsequent collaborative processes and outcomes).[6,8,55,75,84] For instance, Trochim and colleagues[6] offered an empirically derived logic model (based on the NCI TTURC initiative-wide evaluation study) that accounts for the temporal links observed between the early processes of intellectual collaboration and integration, on the one hand, and subsequent team products—including scholarly publications, transdisciplinary training programs, community health interventions, and public-policy initiatives—on the other; and in this supplement, Holmes et al.[34] and Hall et al.[40] present multistage conceptual frameworks that have guided transdisciplinary research, training, and community intervention efforts within the NCI CPHHD and TREC initiatives, respectively.

Earlier, Stokols and colleagues[31,76] proposed an antecedent–process–outcome model of transdisciplinary science in which several interpersonal, environmental, and organizational antecedents of collaboration are considered, such as the leadership styles of center directors, scientists' commitment to team research, the availability of shared research and meeting space, electronic connectivity among team members, and the extent to which they share a history of working together on prior projects. The intervening processes examined in this model included intellectual, interpersonal, and affective experiences as well as observed or self-reported collaborative behaviors, or both. Examples of these processes are the brainstorming of strategies to create and integrate new ideas, to deal with the cross-disciplinary biases and tensions that often arise in collaborative situations, and to negotiate and resolve conflicts. The antecedent and process variables specified in the model, in turn, influence several near-, mid-, and long-term outcomes of scientific collaboration, including the development of new conceptual frameworks, research publications, training programs, and translational innovations over the course of the initiative. Empirical support for the hypothesized links among antecedent, process, and outcome variables was derived from a longitudinal (5-year) comparative study of the TTURC centers.[31,62,75,77]

Existing models of interdisciplinary and transdisciplinary collaboration raise several questions for future research. For example, certain antecedent conditions present at the outset of a team science project can be conceptualized as collaboration-readiness factors that jointly influence a team's prospects for success over the course of an initiative.[36,40,75] However, the relative contributions of individual collaboration-readiness factors (e.g., the leadership skills of center directors, the availability of shared office and laboratory space, team members' experiences working together on earlier projects) to specific dimensions of collaborative effectiveness (e.g., the quantity of team publications produced as well as their integrative quality and scope, the development of sustainable partnerships with community organizations) are not well-understood and warrant further study.[39]

Also, earlier conceptual models and the field studies on which they are based suggest that the intellectual and scientific outcomes of team science initiatives are strongly influenced by social and interpersonal processes, including team members' collaborative styles and behaviors, interpersonal conflicts, and negotiation strategies.[6,27,75,85] Yet the precise ways in which these social processes influence scientific productivity and transdisciplinary integration are not known. For instance, team members' disagreements about scientific issues may enhance collaborative effectiveness by stimulating new insights and countering tendencies toward "groupthink" among individuals who have worked together for extended periods.[86] On the other hand, long-standing scholarly disagreements that provoke interpersonal conflict can undermine members' trust of each other and their overall performance.[87,88] The empirical relationships between the interpersonal and intellectual dimensions of scientific collaboration remain to be elucidated in future studies.

Methodologic and Measurement Issues

A variety of methods and measures have been used to assess the antecedents, processes, and outcomes of team science initiatives. The most useful or strategic are those that efficiently apply evaluation resources to yield information about the major contributions and limitations of particular programs in a manner that is responsive to the needs of multiple stakeholder groups, including participating scientists and trainees, funding organizations, policymakers, and translational partners in clinical settings and community organizations.[9] Evaluations of team science programs are embedded within overlapping spheres of influence encompassing organizational, institutional, community, regional, national, and global levels, with multiple stakeholders situated at each level.[29,41,42,89] Strategic evaluations incorporate the diverse perspectives of team science interest groups and adopt some or all of the methodologic strategies mentioned below.

Weighted measures of program success. Strategic evaluations begin with a clear vision of what constitutes success within a particular initiative. For example, NCI research and training center initiatives (TTURC, CECCR, CPHHD, TREC) include multiple goals and objectives, ranging from the achievement of: (1) scientific advances in a targeted area of research (e.g., cancer communications or tobacco-use research) resulting from collaborative synergies within and across participating research centers; (2) innovative approaches to and intended outcomes of transdisciplinary research training; (3) translations of scientific research into useful and sustainable clinical practices and community health programs; (4) translations of scientific research into innovative health-policy initiatives; and, ultimately; (5) reductions in health-risk behaviors, health disparities, and the incidence of chronic diseases within a particular population.[9] The relative priorities assigned to these goals may vary from one initiative to another. Thus, evaluations of team science initiatives are most strategic when the criteria for judging program effectiveness are selected and weighted to reflect the highest-priority goals of the particular programs established by funding agencies and other stakeholder groups (e.g., participating scientists, community members, and [in the U.S.] the DHHS and Congressional oversight committees).[29]

Multimethod evaluation. The diversity of goals encompassed by team science initiatives requires the use of multiple quantitative and qualitative methods to measure their intended processes and outcomes as well as to document their unintended ones. The methods used may include surveys and interviews of team members; behavioral observations of centerwide and initiative-wide meetings and collaborative discussions; archival analyses of scientific productivity and impact based on content analyses of written products developed by team members and bibliometric assessments of initiative-based publications; focus-group meetings among scientists, trainees, and staff members participating in an initiative; online diary logs of cross-disciplinary encounters; social-network analyses of collaborative exchanges; and peer reviews by external referees obtained through periodic site visits and independent evaluations of progress reports and collaborative publications. The combined use of survey, interview, observational, and archival measures in evaluations of team science initiatives affords a more complete understanding of collaborative processes and outcomes than can be gained by adopting a narrower methodologic approach.[6,40,83]

Temporal sequencing of evaluative measures. In addition to establishing prioritized criteria for gauging the scientific, training, translational, and public health outcomes of an initiative, attention should be paid to the temporal patterning of evaluation measurements, ranging from assessments of antecedent conditions present at the outset of a collaborative project to early-stage indicators of collaborative synergy and innovation, mid-term markers of scientific and training innovations, and long-term societal (e.g., policy and public health) outcomes.[90] The latter categories of outcomes may be so gradual or temporally lagged that they are not detectable during the period in which an initiative is actively funded.[32] Future studies should be undertaken to assess the postfunding impacts of team science initiatives on science, training, and public health over extended periods (e.g., encompassing one or more decades).[39]

Research design and sampling issues. Team science initiatives pose several challenges related to the sampling of participants and respondents, the establishment of appropriate comparison groups with which to compare initiative-based research centers and teams, and the implementation of field experimental or quasi-experimental research designs. Experimental and quasi-experimental evaluations of team science initiatives are difficult to achieve due to the nonrandom self-selection of scientists into collaborative teams. Appropriate comparison groups may involve teams of scientists working in a particular area of health research (e.g., tobacco science, cancer communications) that applied for a team–center grant and received "nearly fundable" evaluation scores but were not among those applicants funded to establish a transdisciplinary research program. Prospective evaluations of team science initiatives require sufficient numbers of initiative-based research teams and relevant comparison groups, all of which are working in a common research area over the same multiyear period.

To date, the science-of-team-science field has relied almost exclusively on retrospective and prospective case-comparison studies rather than on experimental or quasi-experimental evaluations of research teams, centers, and the multisite initiatives in which they participate. However, longitudinal bibliometric and social-network analyses incorporating multiple comparison groups are currently being implemented at NCI to evaluate the quantitative and qualitative differences in the productivity of health scientists (e.g., tobacco-use researchers) who are working individually on R01 grants, participating in non-initiative–based research centers, or collaborating as members of transdisciplinary team science initiatives. The increasing use of quasi-experimental research designs incorporating multiple comparison groups is an important direction for the science-of-team-science field.[39]

Convergent validation of evaluation data. Regardless of the research designs used to assess program effectiveness, the convergent validation of empirical data is an important benchmark of strategic evaluation. When evaluations of team science initiatives are conducted, the survey and interview assessments of program outcomes offered by participating scientists, trainees, and staff members should be supplemented with peer appraisals provided by external reviewers and consultants. Additional challenges inherent in peer reviews of team science initiatives are discussed by Klein in this supplement[27] and by Laudel.[54]

Translational Strategies

Within the science-of-team-science field, translational strategies can be grouped into two general categories: (1) the use of research findings from team science initiatives as a basis for developing improved clinical practices, disease-prevention strategies, and public health policies; and (2) the use of research findings from the evaluations of team science initiatives as a basis for enhancing the effectiveness of future collaborative research and training programs. Examples of these two kinds of translational research are outlined below.

Translating research findings from team science initiatives into clinical and preventive practices. The NCI SPOREs and the CPHHD initiative emphasize translational research in which scientific findings are used to improve the prevention, detection, diagnosis, treatment—or all of these—of human cancer and to reduce health disparities in medically underserved populations.[34,63,64] Similarly, utilizing research evidence for the improvement of healthcare delivery is a core goal of the NCRR CTSCs.[13] The scientific discovery processes associated with team science initiatives are the initial phase of a transdisciplinary action–research cycle in which team science investigators work closely with community health practitioners and policymakers to translate their findings into improved therapeutic and preventive practices.[55] Community-based coalitions consisting of health scientists and practitioners and intersectoral partnerships between public and private organizations provide the collaborative contexts in which research findings produced by scientific teams are eventually translated into practical applications.[3,43,91] Examples of university–community partnerships that have produced effective and sustainable translations of cancer research findings into community health promotion and disease-prevention strategies are described by Emmons et al.[44]

Translating research findings from team science evaluation studies to enhance future initiatives. This second category of translational research applies the findings from team science evaluation studies to improve the design and effectiveness of ongoing and future collaborative research and training programs. In the case of ongoing initiatives, formative evaluation strategies can be used for continuous quality improvement by providing team science participants with regular (e.g., quarterly, annual) feedback about their collaborative processes and outcomes.[31,92,93] When future team science initiatives are designed, collaboration readiness audits based on the findings from the evaluations of prior team science programs can be administered to assess a team's prospects for collaborative success and to identify opportunities for strengthening institutional and environmental supports for cross-disciplinary research and training.[75] Also, workshops and training modules can be implemented to familiarize researchers and trainees with the challenges inherent in team-based projects and the steps they can take to improve their chances for success. These translational strategies contribute toward building greater capacity for scientific collaboration in team science initiatives.[40]

Earlier research on team performance suggests that the structural complexity of team science initiatives is closely related to the collaborative challenges and coordination constraints encountered by team members.[36] Collaborative research and training programs that span multiple organizations, geographic sites, scientific disciplines, and levels of analysis may require greater institutional and organizational investments in collaboration-readiness resources to ensure programmatic success than those that are less complex.[55] The empirical links among program complexity; collaboration readiness; and cumulative research, training, and translational outcomes of team science initiatives should be examined in future studies.

Goals and Organization of This Supplement on the Science of Team Science

The present supplement is based on the proceedings of the NCI Conference on the Science of Team Science held in Bethesda MD during October 2006, cosponsored by the NCI, the NIH OBSSR, and the American Psychological Association.[33] The purposes of the NCI conference were to address ambiguities and gaps in the science-of-team-science literature, promote greater integration of knowledge in this field, and identify key issues for future investigation. As a prelude to this event, the NCI convened a group of science-of-team-science scholars in October 2005 to assess the state of the knowledge in the field, identify the most pressing questions for future study, and articulate major goals and strategies for the 2006 conference. The intent of the planning meeting was to build on and go beyond the issues addressed in earlier scholarly discussions of the implementation and evaluation of large-scale, cross-disciplinary science and training programs (e.g., National Academy of Sciences [NAS] Convocation on Facilitating Interdisciplinary Research; NAS Conference on Bridging Disciplines in the Brain, Behavioral, and Clinical Sciences; National Research Council Conference on Interdisciplinary Research; NIH Bioengineering Consortium Symposium on Catalyzing Team Science).[5,21,94,95] In particular, participants were asked to identify cutting-edge issues and themes that had received relatively little attention in prior meetings and research and to draft an agenda of high-priority questions for future study.

During the day-long discussions at the 2005 planning meeting, it was decided that the 2006 meeting would incorporate structured panel sessions organized around the conference themes; peer-reviewed poster presentations; opportunities for informal discussion; and a series of commissioned papers to address high-priority research, training, and translational questions for future investigation.[33] The commissioned papers were intended to integrate existing knowledge in the science-of-team-science field and to open new avenues of research on a variety of previously neglected topics. These high-priority topics for future research are addressed in the articles presented in this supplement and are outlined below.

Developing Integrative Conceptualizations of Team Science Processes and Outcomes

Earlier conferences and publications revealed important facets of team-based science and training (e.g., institutional strategies for facilitating cross-disciplinary research, metrics for evaluating collaborative processes and outcomes), but the findings from science-of-team-science studies remain relatively disjointed and lack theoretical grounding and interpretation. Some research reports go relatively unnoticed as chapters in edited volumes published in several different countries or as reports posted on websites that remain unknown to many science-of-team-science scholars. Sorely needed are new conceptualizations of the science-of-team-science field that are informed by an international perspective and by integrative frameworks for organizing and interpreting the findings from prior studies. Klein's article[27] addresses these needs by offering an integrative approach to the evaluation of interdisciplinary and transdisciplinary collaboration—organized around seven core principles or themes—and an integrative assessment of empirical knowledge in this field, viewed from an international perspective. Additionally, the present article and the ones by Kessel and Rosenfield,[38] Croyle,[9] and Syme[35] in this supplement provide overviews of the science-of-team-science field in terms of its major research, training, and translational concerns, and identify for future investigation several topics that have received little attention in prior studies.

Implementing Team Science Initiatives Selectively and Strategically

Earlier studies[10,31,36,55] suggest that cross-disciplinary team research centers and programs are not uniformly successful. In some situations, smaller-scale unidisciplinary projects may be more feasible and likely to succeed than larger, team-based initiatives. Also, certain research questions may be more amenable than others to interdisciplinary and transdisciplinary approaches. Thus, cross-disciplinary collaboration should be viewed as a means for achieving the desired scientific, training, and translational goals rather than as an end in and of itself. That is, investments in team-based initiatives should be reserved for those settings and research topics that are most suited to and would benefit most from collaborative approaches. An important goal for science-of-team-science research is to facilitate "smarter" science, in which particular approaches (e.g., single-investigator versus team-based projects; unidisciplinary versus multidisciplinary, interdisciplinary, or transdisciplinary initiatives) are closely matched to the unique talents and predilections of the participating scientists, the institutional contexts in which they work, and particular research topics and fields (some of which may be more amenable to cross-disciplinary integration than others, as noted by Hays[45]).

Yet conceptual frameworks that enable researchers and their host organizations to forecast when and where team science initiatives will be more or less effective have been lacking. Accordingly, the ecology of team science by Stokols and colleagues[36] in this supplement is intended to provide an integrative typology of contextual factors that have been found to jointly influence collaborative effectiveness across a variety of research and community settings. The typology is based on a review of empirical findings from the fields of social psychology, organizational behavior, information science, community health promotion, and team science evaluation. It offers a conceptual starting point for developing more fine-grained analyses of high-leverage variables (i.e., those that most strongly determine the success of team-based initiatives). Examples of contextual factors that appear to be especially strong determinants of collaborative effectiveness in research settings are discussed below.

The Impact of Interpersonal Processes and Leadership Styles on Scientific Collaboration

Prior evaluations of team science initiatives suggest that the social organization of research teams strongly influences their capacity to achieve scientific or intellectual integration.[6,27,36,75] Several interpersonal processes may directly influence collaborative effectiveness in research settings. To the extent that team members have worked together previously and share a strong commitment to scientific collaboration, they may be better able to coordinate their efforts and accomplish their research, training, and translational goals in subsequent team science projects.[31,40,76] On the other hand, interpersonal conflicts among team members (especially those persisting over long periods) undermine mutual trust and hinder collaborative processes and outcomes.[10,85,88,96] Among the factors that most strongly influence the quality of social interactions in collaborative settings are the abilities and styles of team leaders. Although the links between leadership and collaborative effectiveness have been studied extensively in nonscientific settings,[97–100] they have received relatively little attention in the science-of-team-science field. This gap in science-of-team-science knowledge is directly addressed in the supplement article by Gray,[46] who offers an empirically based conceptualization of three types of leadership tasks that promote transdisciplinary collaboration among leaders of scientific teams. Her analysis of the ways in which leadership styles and abilities influence scientific collaboration provides a conceptual foundation for future research on this topic.

Another important facet of scientific collaboration are the social networks that exist among researchers and the ways in which they influence patterns of communication and cross-disciplinary integration. The article by Provan and colleagues[42] summarizes an empirical study of social networks among scientists working in the field of tobacco harm reduction. Communications among participating tobacco harm–reduction scientists from multiple fields that involve only exchanges of information are considered interdisciplinary, whereas those that lead to the creation of synergistic products (e.g., multi-authored publications) are defined as transdisciplinary. The analyses of network data provided by Provan et al. reveal that homophily, or the tendency to interact with others whose backgrounds are similar to a person's own (evidenced by intradisciplinary network ties), is more prevalent than heterophily (defined as cross-disciplinary communications among network members). Moreover, nonsynergistic interdisciplinary interactions are much more common than transdisciplinary transactions that result in collaborative research outcomes. These data, along with the findings from earlier research, highlight scientists' strong tendencies to affiliate with colleagues whose disciplinary perspectives are similar to their own, and the need to better understand the circumstances under which scientists achieve and sustain cross-disciplinary collaboration and integration.[75,101]

Developing Cyber-Infrastructures to Support Scientific Collaboration

Interpersonal processes (e.g., communication networks, conflict-resolution strategies, leadership styles) are contextual factors that directly influence a team's readiness for collaboration at the outset of a project and their capacity to work together effectively over extended periods. Additional determinants of collaborative capacity and long-term success are the technologic resources (e.g., intranet and Internet connectivity, grid computing infrastructures, data-mining strategies) that enable team members to communicate and integrate diverse sets of data effectively over the course of a team science project.[102] These facets of technologic infrastructure and expertise and their influence on scientific collaboration have received attention in the fields of information science and organizational behavior, but warrant further investigation in the context of team science research and training programs.[36] The ways in which cyber-infrastructures can support successful scientific collaboration spanning multiple disciplines and research sites, and an agenda of related questions for future science-of-team-science studies, are discussed by Hesse in this supplement.[47]

Conceptualizing and Measuring Distinctive Features of Cross-Disciplinary Training

On the one hand, distinctions among multidisciplinary, interdisciplinary, and transdisciplinary forms of cross-disciplinary (versus unidisciplinary) research have received considerable attention among science-of-team-science scholars. On the other hand, these same distinctions, as they relate to strategies of cross-disciplinary training, have been relatively neglected.[62,82,83] Nash's article[37] in this supplement confronts current gaps in the understanding of cross-disciplinary education by offering a broad conceptualization of multidisciplinary, interdisciplinary, and transdisciplinary training and their respective goals. Compared to multidisciplinary and interdisciplinary approaches, transdisciplinary training is uniquely defined by its intention to produce scholars who synthesize theoretical and methodologic perspectives spanning multiple disciplines and analytic levels. Nash distinguishes among different forms of transdisciplinary training, including single-mentor and team-mentoring apprenticeship models, and transdisciplinary training programs that are either broad or narrow in their analytic scope (e.g., in which trainees learn to integrate the perspectives of disciplines sharing the same or widely different levels of analysis). Nash also outlines intrapersonal, interpersonal, and systems-level constraints on—as well as facilitators of—transdisciplinary training processes and outcomes. Finally, his analysis highlights the importance of developing new methods and metrics for evaluating transdisciplinary training, and suggests new directions for research in this area.

Translating Team Science into Effective Clinical, Community Health, and Policy Initiatives

Many large-scale team science initiatives are designed to foster translations of scientific knowledge into improved clinical practices, community health outcomes, and public policies (e.g., statewide taxation of cigarette sales).[13,63,64] However, the processes by which scientific evidence from team science initiatives is incorporated into clinical and community-based programs for health improvement are not well understood.[3] A useful starting point for the development of community-based health initiatives is the transdisciplinary integration of research findings on a particular topic drawn from multiple fields and levels of analysis. For instance, Hiatt and Breen's article[19] in this supplement offers a broad-gauged transdisciplinary synthesis of research evidence documenting the role of social factors in cancer etiology and the ways in which social, behavioral, psychological, and biologic variables as well as the healthcare system jointly influence cancer incidence, survival, and mortality rates. Hiatt and Breen's analysis provides conceptual grounding for developing more comprehensive strategies of cancer prevention and control than have been available in the past.

Emmons and colleagues[44] describe several cases in which the scientific findings obtained through team science initiatives at a university-based cancer center were translated into novel health-communication programs for disease prevention. Examples of these translational initiatives are the Harvard Colorectal Cancer Risk Assessment and Communication Tool for Research and two public Internet sites, Your Cancer Risk and Your Disease Risk.[103] Emmons and colleagues note that the features and functionality of these award-winning websites were influenced by transdisciplinary collaboration among scholars from several different fields. They also describe other translational programs designed collaboratively with non-university partners through community-based participatory research strategies,[104] including the Massachusetts Community Network for Cancer Education, Research, and Training. Taken together, the supplement articles by Hiatt and Breen[19] and Emmons et al.[44] highlight the value of transdisciplinary research findings and conceptual frameworks as a basis for developing novel and sustainable interventions for disease prevention.

Improving the Transfer of Knowledge Across Team Science Initiatives and Evaluation Studies

Another type of translational challenge facing the science-of-team-science field is to improve the transfer of knowledge across multiple initiatives and evaluation studies. Too often, the lessons learned over the course of an initiative are not effectively communicated or transferred to other research organizations and scientists who are contemplating or already engaged in subsequent team science programs.[6,9,75] Investments in team science evaluation studies become more cost effective and strategic to the extent that their conceptual integrations, empirical findings, methodologic tools, and translational innovations are made available to current or prospective members of other initiatives. Hiatt and Breen's analysis[19] of social factors in disease etiology exemplifies a conceptual tool that can be used to guide future research, training, and translation initiatives in the field of cancer control. Similarly, Holmes and colleagues[34] summarize several methodologic lessons learned through their multilevel analyses of health disparities that can be of benefit to participants in future transdisciplinary team science initiatives.

Similarly, new methods and metrics for gauging the effectiveness of a particular team science program can be used later to guide the design and evaluation of other team initiatives once their reliability and validity have been established. The development of new methods for evaluating team science is the focus of two additional articles in this supplement. Hall and colleagues[40] present initial findings from the 2006 NCI TREC Year-One evaluation study in which a new online survey protocol was developed to assess the levels of institutional and interpersonal readiness for transdisciplinary collaboration during the early stages of a 5-year initiative. Empirical links among several dimensions of collaborative readiness, including the availability of shared research facilities; investigators' history of working together on prior projects; and their endorsement of unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary research perspectives, were examined in this study. Also, Mâsse and colleagues[48] summarize new analyses of survey data obtained from tobacco scientists participating in the first 5-year phase of the NCI TTURC initiative. The survey measures and the findings from this study—conducted as part of the NCI evaluation of large initiatives (ELI)[6,31]—exemplify new tools for assessing the impact of interpersonal processes (e.g., collaborative experiences and behaviors) on scientific integration and productivity. These methods and metrics are potentially applicable to the evaluations of other initiatives.

Finally, Kessel and Rosenfield[38] provide a broad review of earlier transdisciplinary research, training, and translational programs as a basis for identifying insights and guidelines that can be used to improve the design and evaluation of future initiatives. Their findings are directly relevant to the goal of enhancing the transfer of knowledge from prior team science initiatives and evaluation studies to subsequent ones.

Understanding the Systemic Contexts of Team Science Initiatives and Their Evaluation

Another relatively neglected topic within the science-of-team-science field is the influence of systemic factors (e.g., institutional supports for interdisciplinary and transdisciplinary collaboration, public and private investments in large-scale research initiatives, societal concerns about the accountability of scientific research) on the design, functioning, and evaluation of team science initiatives.[29,42,89] These issues are addressed in several of the supplement articles. Leischow and colleagues[41] present an overview of systems theory and the ways in which systems thinking can be used to promote public health. A key principle of systems theory is that socio-technical systems (e.g., team science research initiatives) are embedded within broader systemic units (e.g., the Division of Cancer Control and Population Sciences [DCCPS] of NCI) that administer several large initiatives that in turn are nested within larger entities and spheres of influence (e.g., the NIH).[105,106] An advantage of systems thinking is that it reveals the interdependencies among systemic units that operate at these different levels.

For instance, Croyle[9] describes four large-scale transdisciplinary research and training initiatives (TTURC, CECCR, CPHHD, TREC) that are directed by DCCPS within NCI. Because DCCPS serves as the coordinating unit for these programs, lessons learned from the evaluations of the first initiatives to be implemented (TTURC and CECCR) have been incorporated into the design of subsequent programs (CPHHD and TREC).

This transfer of knowledge among several large-scale initiatives has the potential advantage of enhancing the cost effectiveness of DCCPS's and NCI's investments in transdisciplinary science and training programs.

At a broader institutional level, the article by Hays[45] in this supplement (and the papers presented by Farber[107] and Kington[11] at the 2006 NCI conference on the science of team science) describe the NIH Roadmap and OPASI initiatives, both of which are intended to promote greater integration among the disciplines represented within the various institutes that constitute NIH. The design and mission of these initiatives have been informed not only by health research and the assessments of the scientific readiness[45] of particular fields for transdisciplinary integration, but also by societal concerns about public health and the accountability of science to society as a whole.[9,14] Both the Roadmap and OPASI initiatives encompass several other interrelated team science research and training programs, coordinated by multiple institutes at NIH, whose goals are closely aligned with the Roadmap initiative's emphasis on transdisciplinary scientific integration, training, and translation (e.g., the ambitious Clinical Translational Science Awards initiative).[13,29,74] The Roadmap and OPASI initiatives thus provide a strategic framework and mission for organizing several subsidiary team-based programs.

Also within the context of the NIH, Mabry and colleagues[49] describe the strategic mission and cross-disciplinary initiatives supported by OBSSR. Systems principles drawn from the fields of social ecology, populomics, and informatics have been integrated with the biomedical concerns of the Human Genome Project and incorporated into the various programs administered by OBSSR.[16,108–111] The broad biopsychosocial and ecologic vision reflected in OBSSR's strategic plan exemplifies an application of systems thinking to broaden the conceptual scope, the positive health impacts, and the cost effectiveness of large-scale transdisciplinary initiatives.

Federal funding agencies such as the NIH are but one of several potential contributors to the development of transdisciplinary health science and the improvement of public health outcomes. Shen's article[43] in this supplement calls for the establishment of cross-sectoral team science, and underscores the importance of forging new collaborative relationships among private corporations and foundations, public research agencies, and nongovernmental organizations for the purpose of funding and sustaining transdisciplinary health science and improving public health. This is an exciting and potentially fruitful direction for the science-of-team-science field.

The concluding article by Hall and colleagues[39] recaps major themes reflected in the supplement and identifies promising directions for future research organized around key programmatic challenges related to the refinement of science-of-team-science terminology, conceptual frameworks, research methods, transdisciplinary training strategies, cross-sectoral partnerships, and sustainable funding mechanisms. For instance, it will be important in future science-of-team-science research to more clearly conceptualize and measure the construct of readiness for collaboration. This concept has been defined variously in terms of individual and group research orientations,[40,69] organizational and technologic resources that enhance capacity for collaboration,[36,47,57] and the scientific readiness of different fields for collaborative integration.[41,45] Yet, as Hall et al.[39] observe, little is currently known about how these different dimensions of collaborative readiness jointly influence the effectiveness of transdisciplinary initiatives.

Summary

The preceding discussion offers an overview of the science-of-team-science field in terms of its major conceptual, methodologic, and translational concerns. This field encompasses a wide array of research projects and strategies aimed at better understanding, evaluating, and managing circumstances that influence the effectiveness of large-scale team science initiatives. Common themes are beginning to emerge in the literature, but several gaps in the science-of-team-science knowledge base remain to be addressed in future studies. The 2006 NCI conference on the science of team science and the present supplement were organized for the purposes of identifying and analyzing several cutting-edge issues that had received little or no attention in prior science-of-team-science meetings and publications. It is hoped that the articles included in this supplement will help to establish the foundation for achieving greater clarity and integration in science-of-team-science research and for advancing the field's scientific, training, and translational goals.

This article is based on a paper presented at the NCI conference on The Science of Team Science: Assessing the Value of Transdisciplinary Research on October 30–31, 2006, in Bethesda MD. The authors gratefully acknowledge support for this manuscript provided by an IPA contract to Daniel Stokols from the Office of the Director, DCCPS of the NCI; and by Cancer Research Training Award fellowships to Kara L. Hall and Brandie K. Taylor.

No financial disclosures were reported by the authors of this paper.

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