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The Science of Team Science: A Review of the Empirical Evidence and Research Gaps on Collaboration in Science

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Collaborations among researchers and across disciplinary, organizational, and cultural boundaries are vital to address increasingly complex challenges and opportunities in science and society. In addition, unprecedented technological advances create new opportunities to capitalize on a broader range of expertise and information in scientific collaborations. Yet rapid increases in the demand for scientific collaborations have outpaced changes in the factors needed to support teams in science, such as institutional structures and policies, scientific culture, and funding opportunities. The Science of Team Science (SciTS) field arose with the goal of empirically addressing questions from funding agencies, administrators, and scientists regarding the value of team science (TS) and strategies for successfully leading, engaging in, facilitating, and supporting science teams. Closely related fields have rich histories studying teams, groups, organizations, and management and have built a body of evidence for effective teaming in contexts such as industry and the military. Yet few studies had focused on science teams. Unique contextual factors within the scientific enterprise create an imperative to study these teams in context, and provide opportunities to advance understanding of other complex forms of collaboration. This review summarizes the empirical findings from the SciTS literature, which center around five key themes: the value of TS, team composition and its influence on TS performance, formation of science teams, team processes central to effective team functioning, and institutional influences on TS. Cross-cutting issues are discussed in the context of new research opportunities to further advance SciTS evidence and better inform policies and practices for effective TS.

Keywords: science of team science, research collaboration, interdisciplinary, cross-disciplinary, team processes

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Scientific and societal challenges are becoming more complex, and efforts to address them require research collaborations across disciplinary, organizational, and geographic boundaries. Meanwhile, rapid changes in science and technology, including unprecedented increases in disciplinary specialization, global scientific output, data capture, and computing capabilities, create both opportunities and challenges for capitalizing on scientific knowledge. Further, recent advances in communication and data sharing technologies enable scientists to work virtually in ways that were unimaginable just a few decades ago.

These trends necessitate advances in how we conduct and support research. One approach in need of systemic advance includes team science (TS). Across virtually all fields, research is increasingly being done in teams (Wuchty, Jones, & Uzzi, 2007), with some of the most complicated collaborations - multi-university collaborations - growing the fastest (Jones, Wuchty, & Uzzi, 2008). TS refers to the approach of conducting research in teams within complex social, organizational, political, and technological milieu that heavily influence how that work occurs.

Although TS holds great promise for accelerating scientific progress, collaboration in science is complex. It requires evidence-based strategies as well as strategic changes across the scientific enterprise to fully realize its potential (Börner et al., 2010; Fiore, 2008; Stokols, Misra, Moser, Hall, & Taylor, 2008). Reflecting these needs, funders and universities aim to invest in strategies that align with evolving demands in science, yet leaders struggle to know whether, when, and how to best support TS endeavors. Administrators often question the *added value of TS* (e.g., "Do cross-disciplinary teams produce higher impact science than unidisciplinary teams or solo investigators?") and offer skepticism regarding *the best ways to support science* (e.g., "Why fund large TS initiatives? Isn't it more effective to fund smaller investigator-driven grants?"). Scientific leaders express concern about *why TS is not happening effectively* (e.g., "What are the barriers to conducting effective TS?") and *how to improve its effectiveness* (e.g., "What strategies can I use to enhance TS?"). Researchers struggle to understand *the best approaches to forming teams* (e.g., "Who should be part of my team and how do I find them?") and those conducting research in teams want to know *how to do TS better* (e.g., "What strategies should be used to improve team functioning?"). Historically, these questions have been addressed by assembling leaders in science to discuss challenges and successes. Such conversations yield anecdotal evidence that lacks generalizability and may lead to misguided approaches that forestall progress (Hall, 2017). With an estimated $433 billion invested in the United States on research and development in 2013 alone (Harrington, 2016), establishing empirical evidence for effective TS practices and policies is sorely needed.

The Science of Team Science and Allied Fields

In the early 2000s, increasing recognition of the need for evidence-based solutions to advance successful TS inspired the development of a cross-disciplinary (CD) field called the Science of Team Science (SciTS). The launch of the SciTS field can be traced to a conference held at the National Institutes of Health in 2006 (Stokols, Hall, Taylor, & Moser, 2008). Since then, SciTS researchers have advanced the field by developing research agendas with input from key experts (Börner et al., 2010) and stakeholders (Falk-Krzesinski et al., 2011; National Research Council (NRC), 2015) as well as producing a rapidly growing body of literature on science teams.

The SciTS field aims to develop an evidence base including interacting and multilevel factors that influence the effectiveness of science teams and ranging from science policy to psychological factors. It aims to synthesize and build upon methods, concepts, and theories from a range of relevant disciplines and fields. For instance, methods and insights from the study of scientific enterprise, as done in fields like the Science of Science Policy (SciSIP; The Science of Science Policy Council, 2008), offers opportunities to characterize collaborations across disciplines, institutions, and countries, and identify patterns that can help illuminate overarching trends to inform our understanding of the value of TS. Economics offers theories and insights related to issues such as resource agglomeration and distribution of labor in science collaborations operating within and across organizations (Salter & Martin, 2001), which may inform improvements to TS structures and functioning. Decades of research from the organizational sciences pro-

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vides insights on, for example, potential leadership approaches (Day, 2013) that may be adapted for activities such as directing an international research program (e.g., the CERN large hadron collider) or engaging community stakeholders in applied research.

Complementary to the more macrolevel perspectives of fields like SciSIP, the empirical study of groups and teams offers a rich set of theories and principles suited to answering questions related to the effectiveness of science teams. Over the past century, psychologists have studied teams across contexts including laboratories, aviation and military settings, and complex organizational environments (Bell, Tannenbaum, Ford, Noe, & Kraiger, 2017; Guzzo & Dickson, 1996; Mathieu, Hollenbeck, van Knippenberg, & Ilgen, 2017). To a large degree, this domain has been guided by the input-process-outcome model of teamwork (Kozlowski & Ilgen, 2006). This paradigm inspired decades of research in which features of collaboration were examined independently (e.g., individual attitudes) or interdependently (e.g., information sharing and solution identification) to disentangle relationships among concepts and determine how they impact team effectiveness. In more recent years, research on teams has produced dynamic and multilevel analyses that allow for a more holistic understanding of collaboration (e.g., Ilgen, Hollenbeck, Johnson, & Jundt, 2005; Klein & Kozlowski, 2000). Although it is beyond the scope of this article to summarize decades of work in the science of teams, comprehensive reviews provide key considerations for selecting, developing, and maintaining teams (i.e., cooperation, conflict, coordination, communication, coaching, and cognition, composition, culture, and context) (Salas, Shuffler, Thayer, Bedwell, & Lazzara, 2015).

The SciTS field aims to bridge perspectives from the micro to the macro to understand how factors emerging from these levels affect science teams. The scientific enterprise includes unique contextual conditions associated with legacy structures of academia, sources of support, rewards and incentives, success metrics, motivations for collaboration, and collaborators who are also competitors. These introduce opportunities for theories and principles from the general study of teams and other allied fields to be applied to and modified for science teams (Fiore, 2008). Likewise, there are opportunities for the SciTS field to inform and enrich the study of teams and allied fields more broadly. To that end, this article reviews the existing empirical SciTS literature to identify what is known about engaging in TS, highlight gaps in the literature, and suggest future directions for how psychological science can advance the field.

Brief Summary of Review Strategy

A search of the published literature on TS involved three separate approaches. The first included keyword searches of relevant TS terms in three major databases: PsycINFO, Scopus, and PubMed. Second, all articles from two major SciTS-specific community-driven repositories of TS specific articles—the National Cancer Institute's Team Science Toolkit (Vogel et al., 2013) and the Mendeley SciTS Group—were included. Third, additional articles were identified from the reference sections of articles that using met inclusion criteria.

Articles were included based on the following criteria: (a) English-language journal articles published from 2006 (the launch of the SciTS field) through September 2016; (b) quantitative or mixed-methods research studies; and (c) study subjects based in academic, government, or publicly funded settings. Excluded studies were purely qualitative (e.g., interview-based studies, ethnographic studies), limited to student teams within a classroom or teams in any nonscience setting (e.g., industry, military, business, sports), focused solely on the development of TS related methods or measures, and assessed science collaborations descriptively at the field level, without consideration of team processes or other factors influencing scientific output.

Our search strategies produced a total of 3,743 articles for consideration. Titles, abstracts, and full text (as needed) of these articles were then reviewed to identify articles that met the inclusion criteria. A total of 109 articles were determined to be eligible. The study purpose, characteristics of the data source(s) and/or sample, study design, independent and dependent variables, results, interpretations of results, and any indicated future directions for related research were extracted from each article and added to a coding spreadsheet. An inductive data analysis approach was then applied to this content, leading to the distillation of themes that capture the critical developments in this literature.

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Subthemes based on fewer than four related articles are not reported in our primary evidence summary.

Summary of the Quantitative Evidence From the SciTS Field

More than 75% of the 109 articles leveraged preexisting data (e.g., archival, administrative, publication) to answer questions about scientific outcomes (see Table 1). For example, 62% used publication data for bibliometrics (e.g., productivity, scientific impact). Notably, 27% of the articles used network analysis to examine publication and archival data. Over 40% of the studies used traditional social science approaches (e.g., surveys), with more than 10% of the studies including interview or observational techniques.

The review identified five major themes that emerged from the SciTS literature and that are relevant to the needs of funding agencies, research institutions, and science teams. Together, they reflect the scientific and practical questions that have drawn the attention of the SciTS field. In the following sections, we summarize the evidence related to each of these themes: (a) *the value of TS* collaborations that span organizational, geographic, and disciplinary boundaries; (b) characteristics of *team composition* that influence TS performance, including team size and diversity; (c) factors that relate to the *formation of science teams*, including team members' physical proximity and social ties, brokers within teams and networks, and prior experience with collaboration; (d) team processes central to *effective team functioning*, including cognitive, motivational, affective, and behavioral processes; and (e) *institutional and organizational influences on TS*, including resources, coordination mechanisms, and organizational structures.

The Value of Team Science

Value of collaboration across organizational and geographic boundaries. Researchers tend to collaborate with members of their own institutions (Dahlander & McFarland, 2013; De Fuentes & Dutrénit, 2012; Dhand, Luke, Carothers, & Evanoff, 2016; Mayrose & Freilich, 2015), and difficulties introduced because of distance are a common challenge across multiple types of scientific collaborations (Harris, Provan, Johnson, & Leischow, 2012). Yet, despite such challenges the literature shows that scientific collaborations spanning organizational and geographic boundaries generally enhance research impact. Numerous studies have examined research produced by teams that span boundaries, including academic departments (Abbasi & Jaafari, 2013; Bales et al., 2014; Birnholtz, Guha, Yuan, Gay, & Heller, 2013; Jones et al., 2008), institutions (Abbasi & Jaafari, 2013; Jeong & Choi, 2015; Jones et al., 2008; Larivière, Gingras, Sugimoto, & Tsou, 2015; Mayrose & Freilich, 2015), and countries (Abramo, D'Angelo, & Solazzi, 2011; Barjak & Robinson, 2008; Didegah & Thelwall, 2013; Freeman, Ganguli, & Murciano-Goroff, 2014; Jeong & Choi, 2015; Jones et al., 2008; Larivière, Haustein, & Börner, 2015; Sud & Thelwall, 2016). The evidence overwhelmingly suggests that boundary-spanning teams have better outcomes, including greater productivity and scientific impact, compared with less distributed teams or solo scientists. While the evidence generally highlights that scientific collaborations that span organiational and geographical. The evidence also suggests that these outcomes may vary by field of science, among teams with particular configurations, or within specific contexts (Didegah & Thelwall, 2013; Freeman et al., 2014; Onal Vural, Dahlander, & George, 2013; Sud & Thelwall, 2016).

Value of cross-disciplinary integration in teams. The SciTS literature defines "discipline" broadly to include disciplines, fields, professions, and community and policy stakeholders (Hall, Stipelman, Vogel, & Stokols, 2017). CD teams work together to solve a particular scientific problem by integrating concepts, theories, approaches, or methods across more than one discipline. Research shows that both low and very high levels of interest overlap are associated with lower chances of collaboration, whereas moderate to high levels of interest overlap lead to the highest levels of collaboration (Mayrose & Freilich, 2015). Some research shows that CD collaborations are more common in strategic disciplines (e.g., translational), whereas unidisciplinary collaborations occur more frequently in basic disciplines (van Rijnsoever & Hessels, 2011), though other research has found that basic and translational researchers are more likely to join CD teams than clinical care providers (Salazar, Lant, & Kane, 2011).

Generally, studies indicate that CD teams produce more publications and publish in more diverse publication venues

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(Hall, Stokols, et al., 2012; Stipelman et al., 2014; Stvilia et al., 2011), and generate more innovative products than comparison teams (Cummings & Kiesler, 2005; Lee, Walsh, & Wang, 2015; Lungeanu & Contractor, 2015; Misra, Stokols, & Cheng, 2015). Publications that include disciplinary diversity of references are found to be notably impactful (Wang, Thijs, & Glänzel, 2015), with research citing disciplines that are far apart in their knowledge domains (e.g., social science and chemistry) receiving the highest relative citation counts (Larivière, Haustein, et al., 2015). With respect to coauthorship, among medical research articles, those that included one or more coauthors from a basic science department were more likely to appear in high-impact journals than papers with coauthors from clinical departments alone (Bales et al., 2014). Studies assessing different characteristics of disciplinary diversity among team members or ideas represented in publications have identified a curvilinear relationship between degree of scientific heterogeneity and research impact, in which moderate heterogeneity yields the highest impact publications (Onal Vural et al., 2013; Yegros-Yegros, Rafols, & D'Este, 2015).

Team Composition

Team size. Science teams are increasing in size, and solo authorship is declining in nearly all disciplines (Ahn, Oh, & Lee, 2014; Larivière, Gingras, et al., 2015; Wuchty et al., 2007). Larger teams are often more productive (Jeong & Choi, 2015; Larivière, Gingras, et al., 2015) and impactful (Sud & Thelwall, 2016). Some evidence indicates a positive relationship between TS and publication outcomes (productivity, impact, and novelty), yet once certain thresholds are reached, these publications outcomes continue to increase but less proportionately (Abbasi & Jaafari, 2013; Cook, Grange, & Eyre-Walker, 2015; Cummings, Kiesler, Bosagh Zadeh, & Balakrishnan, 2013; Lee et al., 2015). Team size has also been found to be associated with other types of outcomes, for instance, some studies have found that small teams are more likely to generate new disruptive ideas, whereas large teams are more likely to further develop such breakthroughs (Winnink, Tijssen, & van Raan, 2016; Wu, Wang, & Evans, 2017).

Although research from the science of teams suggests there is an ideal team size of six to nine participants, findings from the SciTS literature suggest that ideal team size varies based on a variety of influencing factors, including the disciplines involved, the scientific question(s) being explored, and contextual factors (Adams, Black, Clemmons, & Stephan, 2005; Bonaccorsi & Daraio, 2005; Verbree, Horlings, Groenewegen, van der Weijden, & van den Besselaar, 2015). For instance, some research shows that when the number of institutions involved in a science team within a project increases while the number of authors, countries, or departments does not, citations and readership are reduced (Sud & Thelwall, 2016).

Team diversity. Research has documented certain advantages of diversity among members of a science team (Guan, Yan, & Zhang, 2015; Lee et al., 2015). Yet the literature also suggests that too much diversity on a team can lead to fragmentation and inefficiencies that undermine scientific outcomes (Dahlander & McFarland, 2013; Lungeanu & Contractor, 2015; Misra et al., 2015; Stvilia et al., 2011; Sud & Thelwall, 2016). Few studies have examined cultural and ethnic diversity in science teams. Several studies have demonstrated that ethnic homophily is associated with increased likelihood of coauthorship (Dahlander & McFarland, 2013; Freeman & Huang, 2015), whereas other studies have found that cross-cultural collaborations are associated with higher impact (Barjak & Robinson, 2008; Freeman & Huang, 2015) and display a bell-shaped curve, with moderate levels of cultural diversity producing higher impact publications than either no cultural diversity or very high cultural diversity.

Gender. More than 20% of the studies highlighted findings related to gender in science teams. The overarching finding on impact was that gender diversity in science teams can lead to better outcomes. Studies found that publications by mixed-gender teams receive more citations (Campbell, Mehtani, Dozier, & Rinehart, 2013), and grant proposals that include at least one female collaborator are more likely to be funded (Lungeanu, Huang, & Contractor, 2014). Yet the influence of female leadership on citation impact remains equivocal (Barjak & Robinson, 2008; Jeong & Choi, 2015), and the gender composition of teams appears not to be associated with productivity (Lungeanu & Contractor,

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2015; Stvilia et al., 2011; Vasileiadou & Vliegenthart, 2009).

The literature has found that women engage in more collaborations than men (Abramo, D'Angelo, & Murgia, 2013; Bozeman & Gaughan, 2011; Zeng et al., 2016), particularly outside their own disciplines (Abramo et al., 2013; Lungeanu et al., 2014; van Rijnsoever & Hessels, 2011). Yet patterns of collaboration vary by gender. For instance, women are less likely than men to collaborate with international and industry partners (Abramo et al., 2013; Gaughan & Corley, 2010). Regardless of gender, the likelihood of collaboration may be influenced by family, marital status, and partner employment, though social norms can result in relative bias (Uhly, Visser, & Zippel, 2017). The empirical literature on gender in science is circumscribed by the fact that many areas of research, and many scientific teams, include few, if any, women (e.g., Kegen, 2013; Stvilia et al., 2011). This presents challenges for interpreting the impact of gender on collaboration patterns and outcomes (Benenson, Markovits, & Wrangham, 2014; Zeng et al., 2016). Furthermore, research suggests that recognition and utilization of scientific expertise is not simply contingent on the gender of the scientists but also influenced by the gender of those assessing expertise, as well as female faculty representation in the discipline(s) in which the teams are operating (Joshi, 2014). These and other factors may be at play in explaining gender-based differences in collaboration patterns and outcomes.

Academic rank and professional role. Findings suggest that academic ranks and roles on a team is related to different forms of success. Generally, individuals with higher academic rank collaborate more often and can result in positive outcomes (Bales et al., 2014; Bozeman & Gaughan, 2011; Dhand et al., 2016; Lungeanu et al., 2014; Lungeanu, Sullivan, Wilensky, & Contractor, 2015). The mix of academic ranks and professional roles on a science team influences team outcomes. For example, the involvement of at least one full professor (Bales et al., 2014) or a more senior first author (Stvilia et al., 2011) is associated with greater citation impact, but the contributions of other team members with lower rank and different roles are associated with other favorable outcomes. For example, teams that include technicians, graduate students, or postdoctoral fellows with their own external funding are associated with higher levels of *breakthrough publications*, whereas teams that include graduate students and postdoctoral fellows with project-related funding produce a greater absolute *number of publications*, whereas the inclusion of graduates students is negatively associated with *impact factor* and only postdocs are positively associated with increases in *citations* (Conti & Liu, 2015; Cook et al., 2015).

Formation of Science Teams

Physical proximity. Face-to-face interactions are important in the development of new collaborations. The literature suggests that working in the same department (Dahlander & McFarland, 2013; F. W. Kabo, Cotton-Nessler, Hwang, Levenstein, & Owen-Smith, 2014) or institution (Freeman et al., 2014; Long et al., 2014) is a meaningful contributor to forming new collaborations, and that conference attendance contributes to the development of collaborations over longer distances (Binz-Scharf, Kalish, & Paik, 2015; Freeman et al., 2014; Mahmood, Rowley, & Hartley, 2009). For those who are located within the same institution, path overlap (i.e., overlap in functional space for walking) and physical proximity increase the likelihood of forming a new collaboration and being awarded grants (Binz-Scharf et al., 2015; Kabo et al., 2014; Kabo, Hwang, Levenstein, & Owen-Smith, 2015; Long et al., 2014).

Social ties. Weak social ties (e.g., based on similar research interests or mutual ties) can lead to team formation, whereas strong social ties (e.g., based on history of successful collaboration) can help to sustain teams (Dahlander & McFarland, 2013; Long et al., 2014; Lungeanu et al., 2014; Smith, Lai, Bea-Taylor, Hill, & Kleinhenz, 2016). Network studies have shown that tie strength can negatively affect knowledge creation and suggest that a balance of both strong and weak ties in a science team is critical both to generate novel ideas and advance existing paradigms (Wang, 2016).

Brokers. Brokers connect otherwise isolated individuals and help to diffuse innovative ideas within a network of scientists (Murthy & Lewis, 2015). In general, brokers have higher levels of scientific output (Guan et al., 2015), higher rate of scientific discoveries (Stvilia et al., 2011; Wagner,

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Horlings, Whetsell, Mattsson, & Nordqvist, 2015; Wang, 2016), and greater citation impact (Li, Liao, & Yen, 2013) than others in their networks. Factors such as eminence (Wagner et al., 2015), regularly publishing in top-tier journals, publishing with a variety of different scholars, and publishing over longer time spans are associated with a greater likelihood of serving as a broker, which, in turn, is associated with research impact (Li et al., 2013). Research suggests using research networking (RN) tools which is a potentially viable approach to fill structural holes in a network, in essence can serve to broker connections among researchers and thereby facilitate new collaborations (Vacca, McCarty, Conlon, & Nelson, 2015).

Prior experience with collaboration. Researchers tend to work with past collaborators (Lungeanu & Contractor, 2015; Lungeanu et al., 2015), and this is particularly true when those collaborations were considered successful (Long et al., 2014). Prior experience with collaboration seems to mitigate the potential reduction in research impact that has been associated with a greater number of departments represented by members in a collaboration (Onal Vural et al., 2013). Individuals with a history of prior collaboration are more likely to submit collaborative grant proposals and are more likely to have these proposals funded (Lungeanu et al., 2014). Researchers with prior CD collaboration experience tend to have more collaborators and express greater willingness to participate in future collaborations (Hall et al., 2008; Misra et al., 2015; Salazar et al., 2011; van Rijnsoever & Hessels, 2011). However, studies suggest that years of dealing with challenges to CD TS may diminish interest in future CD TS, particularly in contexts with limited support for CD TS (e.g., tenure and promotion policies that are misaligned with CD TS; Hall, Stokols, et al., 2012; Vogel et al., 2014).

Effective Team Functioning

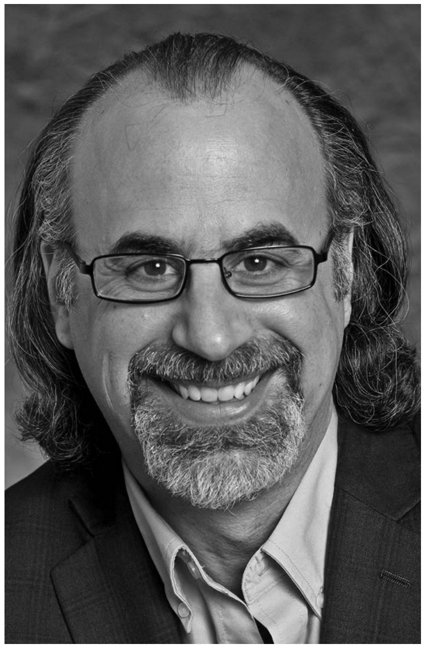
Team processes and emergent states. The teams literature outlines three categories of team processes and emergent states: cognitive, motivational and affective, and behavioral (Kozlowski & Bell, 2013), but only a limited number of concepts within these categories have been studied in science teams.

Cognitive. A key feature of team performance, particularly in CD collaboration, is the development of shared mental models among team members. The use of analogies may surface discrepancies among collaborators' task, process, or scientific mental models, and may be useful to help bridge differences in underlying assumptions in order to facilitate shared understanding (Paletz, Schunn, & Kim, 2013). Physical artifacts created by team members can help to develop shared understanding across disciplinary boundaries by enabling information processing and generating integrated conceptual frameworks for research (Fiore & Wiltshire, 2016; Pennington, 2010). Knowledge sharing, information acquisition, and information dissemination all have a positive effect on team learning, which, in turn, has a positive effect on team performance (Xia & Ya, 2012).

Motivational and affective. When researchers spend more time together at conferences (Binz-Scharf et al., 2015) or as part of a research initiative (Frescoln & Arbuckle Jr., 2015), trust increases. The trust developed by team members can then lead to enhanced knowledge sharing and coordination, and when there are emotional conflicts on a team, knowledge sharing behaviors are reduced (Xia & Ya, 2012). The use of analogies, a key knowledge sharing strategy, may precede or follow conflicts (Paletz et al., 2013).

Researchers with a CD orientation (i.e., those who see the value in working with others and integrating ideas across disciplines) are found to be more closely linked to others in their research networks, and more often serve as brokers (Okamoto & Centers for Population Health and Health Disparities Evaluation Working Group, 2015). Furthermore, they participate in more CD collaborative activities, have more collaborators, report better collaborative productivity, and often garner more institutional resources (Hall et al., 2008; Vogel et al., 2014). In turn, scientists possessing a CD orientation are found to produce more creative and CD publications with greater anticipated translational impact (Misra et al., 2015).

Behavioral. Face-to-face (FTF) communication is important to the success of science teams (Binz-Scharf et al., 2015; Jeong & Choi, 2015; Vasileiadou & Vliegenthart, 2009). FTF meetings—whether at a single institution (Freeman & Huang, 2015; Smith et al., 2016) or at conferences



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(Binz-Scharf et al., 2015; Mahmood et al., 2009)—may be especially important for sparking new collaborations. Successful scientific teams are bolstered by decision making and communication competencies that enhance mutual understanding and facilitate the inclusion of diverse ideas (McGreavy et al., 2015). Among established teams, frequent FTF meetings, whether for team coordination or substantive discussions, supports effective communication and contributes to increased productivity (Vasileiadou & Vliegenthart, 2009) and greater research impact (Jeong & Choi, 2015; Verbree et al., 2015). Coordination behaviors, including division of responsibility for tasks and knowledge transfer among researchers predict a range of project outcomes, such as producing new knowledge, creating new tools, and training students (Cummings & Kiesler, 2007).

The use of technology to communicate (e.g., e-mail, phone and video conferences) may be useful for some project outcomes (e.g., development of new tools or methods) yet may not give scientists an added advantage for others (e.g., productivity; Cummings & Kiesler, 2005; Vasileiadou & Vliegenthart, 2009). Furthermore, the use of other types of technologies (e.g., social media) can be perceived as having low utility in fostering scientific collaboration (Murthy & Lewis, 2015).

Institutional and Organizational Influences on TS

The SciTS literature shows that institutional factors,- including the built environment, organizational structures, and available resources impact both the formation and productivity of science teams. Environmental and spatial factors such as buildings designed to stimulate CD collaboration have been found to increase collaborations (Baumwol, Mortimer, Huerta, Norman, & Buchan, 2011). Institutional initiatives for CD and translational science, such as CD research centers or initiatives, lead to increased CD collaborations (Basner et al., 2013; Baumwol et al., 2011; Bian et al., 2014; Birnholtz et al., 2013; Nagarajan et al., 2015), more highly integrative CD scientific products (Basner et al., 2013; Gowanlock & Gazan, 2013; Hall et al., 2008), more innovative work (Wooten et al., 2015), and heightened productivity (Bishop, Huck, Ownley, Richards, & Skolits, 2014; Hall, Stokols, et al., 2012; Smith et al., 2016). Working groups that welcome diverse opinions and worldviews, facilitate communication, and include knowledge bridging collaborators such as librarians are also found to support CD team performance (Crowston, Specht, Hoover, Chudoba, & Watson-Manheim, 2015).

The availability of resources, in general, facilitates collaboration (e.g., collaborative readiness of scientists; Hall et al., 2008) and is associated with improved productivity (Bishop et al., 2014; Hall, Stokols, et al., 2012), greater impact (Birnholtz et al., 2013; Smith et al., 2016), and the ability to sustain large teams (Adams et al., 2005). Even small amounts of seed funding for pilot projects or retreats can increase in new TS collaborations (e.g., Basner et al., 2013; Birnholtz et al., 2013).

Studies suggest that more complex collaborations may require more robust resources and greater attention to coordination strategies. Without sufficient resources to support teams, productivity can decline, yet projects with greater numbers of universities tend to use fewer coordination mechanisms. Furthermore, multiuniversity projects that use fewer coordination mechanisms yield poorer outcomes (Cummings & Kiesler, 2007). CD teams, in particular, may encounter an initial lag in productivity compared with other research groups (Hall, Stokols, et al., 2012). The observed coordination costs of large team size, CD integration, and cross-institutional collaboration may reflect the extended time and effort needed to develop shared knowledge of one another's disciplinary contributions to the project, shared terminology for the collaborative science, and a mutually agreed upon conceptual model. These costs may also reflect the added leadership, management, coordination, and communication responsibilities involved as well as the work involved to bridging institutional cultures, policies, and procedures across boundaries (Fiore, 2008; Hall, Vogel, et al., 2012; Onal Vural et al., 2013; Vogel et al., 2014).

Forging the Way Forward for the SciTS Field

In this section, we reflect on the state of the empirical SciTS literature by highlighting cross-cutting themes and recommended future directions. We conclude by describing challenges to and opportunities for advancing the SciTS field.

Table 1
Examples of Methods and Measures in Studying Science of Team Science Factors

Factors studied	Methods used	Process/outputs measured	Representative citations
Scientific productivity and influence	Bibliometrics for publication analyses	Publication counts, publication impact, citation counts,	Bales et al. (2014); Conti & Liu (2015); Dahlander et al. (2013); Didegah & Thelwall (2013); Hall, Stokols, et al., 2012; Hormiga, de Saá-Pérez, Díaz-Díaz, Ballesteros-Rodríguez, & Aguiar-Diaz (2017); Huang, Wu, & Wu (2015); Jeong & Choi (2015); Martín-Sempere, Garzón-García, & Rey-Rocha (2008); Onal Vural, Dahlander, & George (2013); Pezzoni, Mairesse, Stephan, & Lane (2016); Taşkın & Aydinoglu (2015)
	Bibliometrics for network analyses	Interdisciplinarity; network brokers, cohesion	Abbasi, Altmann, & Hwang (2010); Stvilia et al. (2011); Wagner, Horlings, Whetsell, Mattsson, & Nordqvist (2015)
	Administrative records	Presentations; grant proposals; published data sets; patents	Costa, Qin, & Bratt (2016); Lungeanu, Huang, & Contractor (2014); Martín-Sempere et al. (2008); Vogel et al. (2012)
Intrapersonal	Surveys	Attitudes about collaboration; perceived changes in research orientation; scientific competencies; future participation in science teams	Baumwol, Mortimer, Huerta, Norman, & Buchan (2011); Crowston, Specht, Hoover, Chudoba, & Watson-Manheim (2015); Frescoln & Arbuckle (2015); Hall et al. (2008); Misra, Stokols, & Cheng (2015); McGreavy et al. (2015); Vogel et al. (2012)
	Archival records	Level of seniority; role	Bales et al. (2014); Stvilia et al. (2011)
Interpersonal	Observation techniques	Conflict	Paletz, Schunn, & Kim (2013)
Organization & management	Surveys	Division of labor; meetings, communication technology; knowledge transfer	Cummings et al. (2007); Walsh & Lee (2015)
Physical & environmental	Public records	Path overlap; physical distance	Kabo, Cotton-Nessler, Hwang, Levenstein, & Owen-Smith (2014)
Scientific creativity intermediate outcomes	Surveys	Scientific innovation and novelty	Toker & Gray (2008)
	Expert evaluations	Scientific integration, innovation and novelty	Hall et al. (2008); Hall, Stokols, et al. (2012); Misra et al. (2015); Wooten et al. (2015)
	Bibliometrics	Cross-disciplinary integration	Basner et al. (2013); Gowanlock & Gazan (2013)

Cross-Cutting Themes and Recommended Future Directions

Impact and productivity of TS. The most frequently studied outcome across this review was research impact (as measured by bibliometrics). Team size is quite consistently and positively associated with research impact. Additionally, particular types of collaborations (e.g., with top tier universities and across nations) and configurations (e.g., inclusion of postdocs and mix of genders) tend to produce more highly cited publications. A variety of individual characteristics of researchers (e.g., brokerage, network centrality) are also associated with greater research impact (e.g., Birnholtz et al., 2013). For instance, prolific authors, eminent scholars, and highly CD-oriented researchers are more likely to have a high degree of centrality in their networks, have more coauthors, and produce higher impact research (e.g., Li et al., 2013; Wagner et al., 2015). These findings indicate that more and unique connections among researchers can introduce greater diversity of perspectives, either directly (via coauthors) or indirectly (through network connections), which can enhance research outcomes. Further research is needed to understand, for instance, if improving connectivity across researchers can increase research impact and whether there are particular characteristics of researchers that enable them to more effectively develop and leverage diverse connections.

Research productivity (e.g., measured by publication counts) also is associated with greater numbers of investigators, disciplines, and institutions in a TS collaboration. And in some cases, a curvilinear relationship is found suggesting that the largest science teams may face unique challenges to research productivity. Dedicated resources are especially important for enhancing productivity, for instance, funding, shared websites and data sets, committed leadership, as well as staff who likely devote a great deal of time to a TS project (e.g., graduate students and postdocs with funding from a given project team) increases productivity (e.g., Cummings & Kiesler, 2007; Verbree et al., 2015). Future research is needed to better understand how specific approaches to implementing research resources, constructing teams, and managing interaction can contribute to achieving particular TS outcomes across contexts.

Taken together, this review suggests that as teams increase in size, the largest teams may experience a marginal degradation of research success, particularly with added diversity, and yet some of the attenuated success may be mitigated with adequate resources and strategic management. A range of tools have emerged to support effective planning for and management of TS, including collaboration planning (Hall, Crowston, & Vogel, 2014), precollaboration agreement templates (e.g., Asencio, Carter, Dechurch, Zaccaro, & Fiore, 2012; NIH Office of the Ombudsman, 2017), and leadership plans for multiple-principle investigator grant applications (NIH Office of Extramural Research, 2017). Opportunities exist to study the effectiveness of such tools as well as further refine them to incorporate new SciTS knowledge.

It is clear that a range of mediators and moderators are at work in influencing team outcomes. For example, as with teams more generally (Salas et al., 2015), dynamic factors such as coordination, communication, trust, conflict, shared goals, and the availability of resources play important roles in team effectiveness and likely play central roles in mediating TS productivity and impact (e.g., Cummings & Kiesler, 2007; Xia & Ya, 2012). To illustrate the potential influences of these factors on TS, we can consider how teams that have worked together to successfully build trust and develop an understanding of who knows what, who does what, and how things get done (i.e., transactive memory; Austin, 2003). In stable, long-term teams, emergent states (e.g., trust and transactive memory) may facilitate high productivity, yet a team's degree of innovativeness may be negatively impacted by fewer new ideas because of a lack of newcomers to the team (Lee et al., 2015). In a similar vein, collaborations among scientists with significant overlap in their areas of expertise may experience challenges to building and maintaining trust, because of competition for resources and reputation, whereas those with little or no overlap in expertise may struggle to effectively communicate their ideas or may experience added conflict because of misaligned goals (Mayrose & Freilich, 2015). Future research on emergent states in TS would benefit greatly from the participation of social science researchers who can enrich this field of inquiry through the development of theoretical models that account for dynamic and contextual factors unique to SciTS (Fiore, Carter, & Asencio, 2015).

Team configuration challenges. There is a paucity of literature on diversity in science teams, particularly when cultural, national, and racial/ethnic diversity are concerned. But the broader teams literature, as well as the SciTS literature on other forms of team diversity (i.e., disciplinary, gender), demonstrates the importance of this factor in shaping team processes, interactions, and outcomes. Composition is also critical, as teams with high levels of diversity may develop fault lines based on subgroup dimensions that influence information sharing. The larger the team and the greater the diversity, the more potential for subgroups to form, which can create interpersonal conflicts (Carton & Cummings, 2013). Emerging research on subgroups highlights different types of fault lines (i.e., identity and knowledge subgroups) of particular relevance to science teams (Carton & Cummings, 2013). This may prove useful for research on team composition, structure, and dynamics, and produce knowledge that can provide guidance for managing fault lines in science teams. Relatedly, opportunities exist for more research on conflict in science teams, particularly by exploring the influences of various forms of conflict, such as task and process conflict (de Wit, Greer, & Jehn, 2012). Tying together these considerations, efforts also are needed to integrate models of team trust and intergroup conflict with models of information sharing (Mesmer-Magnus & Dechurch, 2009) in order to better understand their influences on TS performance. Such work should not lose sight of the contextual issues and variations that are critical to understanding science teams. We can further consider that, as teams increase in size, teams (including subgroups) will need to develop process management strategies. This opens opportunities for considering the inclusion of research on organizational design that can eventually inform practical recommendations for TS (Galbraith, 2012).

Multiteam systems. The size, type, and organization of science teams will be important to consider in future research to develop and apply new practices and policies. For instance, we need to understand how findings translate to support teams ranging in size from 2 to 200 members. We need to identify what additional approaches and recommendations are needed when large numbers of researchers funded together operate as organizations or as multiteam systems (e.g., networks or interrelated centers). To our knowledge, although complex initiatives have been evaluated, no studies have applied theoretical frameworks of multiteam systems to academic research settings to understand the influence of simultaneous interacting processes both within and among teams, such as how interaction processes may benefit the team level but prove detrimental to the multiteam level (DeChurch & Zaccaro, 2013).

Leadership in TS. Despite the importance of strong leadership for TS (National Cancer Institute Team Science Workshop Committee, 2012; Stokols, Misra, et al., 2008) and an emphasis on the need for leadership and management training for scientists (Fiore, 2008; Toker & Gray, 2008), very few quantitative studies have examined leadership in TS. One study revealed that organizational strategies (e.g., acquiring resources) moderated leadership commitment to the group, and leaders with stronger commitment produced more publications (Verbree et al., 2015). In a study of a population of eminent scientists, strategic planning and product championing were key in explaining the positive effects of leadership (Vessey, Barrett, Mumford, Johnson, & Litwiller, 2014).

Although a range of leadership approaches have been identified as potentially relevant to TS (Fiore, 2008; Gray, 2008; NRC, 2015), transformational leadership has been highlighted as a promising approach, in particular, given its potential for facilitating innovation and creativity (e.g., Jung, 2001; Mumford, Scott, Gaddis, & Strange, 2002; Sivasubramaniam, Murry, Avolio, & Jung, 2002). Transformational leadership (a style that inspires and motivates change in a group through the creation of a shared vision and by connecting individuals, project, and organizational identities) was found to have a positive effect on knowledge sharing behavior (Xia & Ya, 2012). Yet interventions devised to improve transformational leadership in science teams were less effective than other process interventions, such as adding new team support roles (Wooten et al., 2015). These findings underscore the need for research on leadership, including training and development.

Training for TS. Training for TS is a growth area, and a variety of approaches are currently being used, including multimentoring training models for graduate students (Vogel et al., 2012), graduate and undergraduate student courses (Khuri & Wuchty, 2015), as well as retreats, workshops, and online trainings that are highly accessible at any career stage (e.g., Spring, Moller, & Falk-Krzesinski, 2011). Although training for TS can ensure researchers have the knowledge and skills critical to success, and although there are many types of TS training strategies (Gehlert, Hall, & Palinkas, 2017), only two articles provide empirical evidence related to TS training (Misra et al., 2009; Vogel et al., 2012), leaving this domain ripe for future study.

Technology. Central to modern TS is the use of technologies to support a range of processes and goals, including how teamwork happens (e.g., sophisticated collaboration software), how collaboration is monitored (e.g., sociometric badges), and how collaboration may be enhanced (e.g., cognitive computing). What is needed is better integration of traditional methods (e.g., biblometrics) with additional measures of interaction, for example, the use of sociometric badges and trace data from collaborative software, to provide a richer understanding of contribution, coordination, and collaboration among researchers. More broadly, the psychological sciences may inform SciTS through a closer examination of science collaboration as sociotechnical systems. For example, human factors psychology has made great strides in developing methods for understanding complex work (e.g., cognitive task analysis; Crandall & Hoffman, 2013) as well as how humans interact with technology (e.g., user studies and human computer interaction research; Boehm-Davis, 2008). More recently, research has led to theoretical and methodological frameworks for studying hybrid human-machine teams and the degree to which technologies can be developed to augment team cognition (Fiore & Wiltshire, 2016). Future research might explore how the use of technology can enhance idea generation in teams and how immersive computer-enabled environments can facilitate effective team interaction (e.g., computer assisted real-time feedback to address conflict or enhance team learning).

The Need for More Sophisticated Study Designs and Methods. A sizable portion of the empirical SciTS literature is descriptive in nature, with a focus on patterns of collaboration. The majority of studies rely on preexisting data and are infrequently guided by theoretical frameworks. This highlights the critical need for more sophisticated designs, including those that are multivariate, examine multiple causal factors, and take longitudinal, experimental, or data intensive approaches (e.g., within-team time series analyses or computationally driven modeling). Moving beyond simple observational designs and linear models to methods that account for the complexity of teams will also increase understanding of the phasic and developmental features of science teams (Hall et al., 2014). Although qualitative studies were outside the scope of this review, these do play an important role in future research for a range of research purposes including theory generation, development of measures and metrics, and the study of complex interacting factors in real-world environments, as through the case study method.

Interestingly, the generally positive outcomes that are found for large, complex science teams seem at odds with the studies of other types of teams (e.g., industry). One possible explanation may be associated with a distinguishing feature of the SciTS research—the dominance of bibliometrics as a primary measure of team performance. And this feature may be particularly influential in studies that use publication authorship teams rather than project teams (or other such types of teams). That is, bibliometric studies based on samples selected from publication databases reflect collaborations that were successful enough to publish. Many researchers are able to act as free agents and choose which collaborations they participate in (if any) and with whom they collaborate, thereby introducing self-selection bias. For instance, researches may choose not to participate in collaborations that they perceive to not align their goals (e.g., to produce publications in high impact journals), or others may choose to avoid partnering with colleagues following unsuccessful collaborations. More research is needed that examines a broader range of teams, for instance, teams that fail to produce publications, struggle to obtain grant funding, or come together and disband before producing any products at all. Additionally, more research is needed that expands the breadth of metrics (e.g., the impact of TS research on clinical guidelines, regulations, and policies) used to assess outcomes of TS both can help to triangulate findings around the added value of TS.

One practical implication of the variations in science teams (composition, size, science, organizational and societal contexts) is that there are no one-size-fits-all prescriptions for effective TS. There is a need for more research to understand the independent and interacting effects of moderating and mediating factors influencing key outcomes in TS. In all of the domains described in the SciTS literature, individuals, teams, institutions, and funders are implementing interventions with the goal of facilitating effective TS. This provides an opportunity for researchers to study these natural experiments. For example, there is a need for assessments of a range of federal funding opportunities that take different approaches to facilitating and supporting TS. Longstanding programs such as the National Academies Keck Futures Initiative, the NIH Clinical and Translational Science Awards, and the NSF Research Coordination Networks, aim to accelerate progress by stimulating CD and cross-institutional TS, each using a unique approach. When team composition and formation are concerned, an increasing number of research institutions are using RN tools to help investigators identify and connect with potential collaborators who have specific expertise needed to address a research goal. These all provide multiple opportunities for future SciTS research, for example, comparing various approaches to identify and engage new collaborators (Boudreau et al., 2017), which, in turn, can help to enhance RN tools (e.g., web-based recommender systems; Contractor & DeChurch, 2011).

These topic areas represent critical areas of interest important to advance the SciTS field, but they do not represent the only opportunities and gaps in the current empirical SciTS literature. For instance, no studies were found that considered areas familiar to psychologists such as individual or team-level personality factors (e.g., Big Five personality traits), nor were any studies identified that addressed issues highly specific to TS such as tenure and promotion policies and practices.

Barriers and Opportunities for SciTS

The SciTS field is recognized as an important area of research by organizations supporting the scientific ecosystem. This includes the National Science Foundation, as evidenced by their support of the National Academies Science of Team Science Committee and the resulting report, *Enhancing the Effectiveness of Team Science* (NRC, 2015), and the National Cancer Institute, through its support of the Team Science Toolkit (Vogel et al., 2013). Yet, to date, there has been limited funding for studying TS in the United States. To illustrate, few of the articles reviewed here cited any funding source for the work reported, with only 15% of the studies report receiving U.S. grant support specifically to conduct SciTS-related research.

Limited funding for SciTS research has hindered the advancement of the SciTS field, both by limiting the number of scholars who are engaged in SciTS research and by influencing the methods they are able to use. This has contributed to an abundance of SciTS studies using freely or easily accessible data such as bibliometrics and administrative data, and this, in turn, has resulted in a focus on TS outcomes dominated by publication metrics. Assessing the scientific and societal impact of team-based research, though challenging, is critical to ensure that science policies and practices maximize our investments in science. Limited resources have also led to the production of studies that have used convenience samples or that have evaluated a single program. These have been important to the development of the SciTS field (e.g., Mâsse et al., 2008; Nagarajan, Lowery, & Hogan, 2011), yet our ability to scale up evaluations will influence the speed of our progress in advancing knowledge of how science teams, across a full range of profiles and contexts, can be maximally effective. Scarce funding also limits the ability for SciTS research to adequately compensate, and thereby engage, scholars from diverse areas of expertise to study TS. Ultimately, to expand our existing knowledge base, and facilitate the development of evidence based practices and policies, the field will benefit from robust CD studies that leverage and potentially integrate approaches, theories, and methods from across disciplines.

Until the SciTS builds a more diverse and robust evidentiary base, caution is needed when considering policy implications. For instance, funding agencies relying on analyses limited to basic grant and publication data, or interpreted based on large volumes of aggregate data, may lead to erroneous conclusions of ideal ways to fund science (Berg, 2017; Kaiser, 2017; Wadman, 2010). Research is needed to understand the merits of bibliometrics as primary indicators for the success of science. Care should be taken when considering policies based on assessments of teams lacking requisite TS competencies or for those operating in contexts misaligned with TS. Furthermore, opportunities exist for funding agencies to conduct prospective studies across the range of mechanisms used to support TS. More comprehensively assessing teams with different profiles and across contexts, as through the application of large-scale longitudinal studies or computational modeling, can inform the development of key science policies, intervention strategies, and organizational changes needed to support successful teams.

Overall, these reflections invoke the tension between the desire to develop one-size-fits-all prescriptions for effective TS, and the need to generate knowledge that can maximally inform practice and policy decisions. Future research should pursue a deeper understanding of TS across the scientific enterprise to help provide guidance on how to support and manage the science that will best serve society.

Conclusion

As the prevalence of TS increases, there is increasing need to advance evidence-based approaches to successfully facilitate and engage in scientific collaboration. The degree to which researchers achieve team-based and integrative science is driven by a complex mix of attitudes, behaviors, and cognition, which, in turn, may be influenced by features of the team, organization, and broader context. The inherent CD nature of the SciTS field requires that varied perspectives from the psychological sciences be brought to bear to enhance understanding of TS effectiveness. The SciTS field is a growing area of research providing insights into the value and principles of scientific collaboration. Much research is still needed to provide a more robust theoretical and empirical foundation, and the psychological sciences are uniquely poised to contribute to the future of TS.

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