The science of team science (SciTS): An emerging and evolving field of interdisciplinary collaboration

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Abstract

In recent years, collaboration within a team to solve complicated scientific and social problems has attracted growing popularity. In particular, many complex challenges and opportunities require expertise and skills across disciplinary, organizational, and cultural boundaries. However, rapid growth in the demand for scientific collaboration has outpaced changes in the factors needed to support scientific teams. Also, scientific results are not simply a combination of different working results; understanding how teams work and what causes them to fail or succeed is of the utmost importance. Thus, the Science of Team Science (SciTS), an emerging interdisciplinary research area, has emerged as a way of understanding and managing the circumstances that facilitate or hinder the effectiveness of large-scale cross-disciplinary, collaborative research, training, and translational initiatives. SciTS integrates various quantitative and qualitative research methods and is still advancing in its sophistication. Using bibliometric and information visualization methods, this paper clarifies the concepts and connotations of teams and team science. It sets out important events in the emergence and development of SciTS and summarizes the characteristics of the SciTS literature, identifying seven main research areas. The paper concludes with a discussion on the challenges facing the future advancement of SciTS and corresponding recommendations for breaking through these bottlenecks. Our goal is to deepen researchers' understanding of SciTS and better inform the policies and practices that govern SciTS for more effective team science.

Keywords

SciTS; Team science; Science of Team Science; Scientific problems; Research teams; Interdisciplinary collaboration; Trends; Evolution; Recommendations; Review article.

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1. Introduction

Scientific research is trending toward greater interdisciplinarity (**Van-Noorden**, 2015) and collaboration (**Wuchty** *et al.*, 2007) as a way of meeting the challenges that confront contemporary society (**Soranno**; **Schimel**, 2014). Compared to the past, scientific problems today are more complex and more unstable –especially problems that affect the fate of all humanity, such as public health, the environment, politics, and policy challenges. Solving these problems requires more than just a simple combination of disciplines. Rather, they need an integrated, interdisciplinary team that can coordinate their efforts in a way that blends knowledge from multiple fields (**Fiore**, 2008). As mentioned in the literature, we are not students of some subject matter but students of problems (**Popper**, 2014). Consequently, "problem-driven" practice is gradually becoming the dominant approach to scientific research, and may cut right across the boundaries of any subject matter or discipline (**Limoges** *et al.*, 1994). It has been shown that efforts to foster greater collaboration among scientists trained in different disciplines are helpful and essential for improving social, environmental, and public health issues (**Hiatt**; **Breen**, 2008).

Interdisciplinary collaboration is essential for scientific discovery and scientific translation (**Bennett**; **Gadlin**, 2012). Some institutions have even established "interdisciplinary research awards" to encourage teamwork and interdisciplinary collaboration. For example, the *NIH's National Center for Research Resources* funds the *Clinical and Translational Science Awards* (*CTSAs*) to bring together researchers from diverse research fields so as to translate scientific discoveries into clinical treatments (**Börner** *et al.*, 2010). Similarly, the *Swiss Academies of Arts and Sciences* has established the *Swiss-Academies Award for Transdisciplinary Research* to reward outstanding contributions to transdisciplinary research (*Swiss Academies of Arts and Sciences*, 2022).

Teamwork and interdisciplinary collaboration can achieve scientific breakthroughs that are not traditionally possible in a single discipline. However, this kind of collaboration can also present many unprecedented challenges. Large team sizes, great diversity among the membership, high task interdependence, deep knowledge integration, permeable boundaries, and geographic dispersion are just a few of the difficulties that need to be overcome. Previously, these problems have been solved by inviting scientific leaders to discuss specific solutions. However, the anecdotal evidence generated by such conversations lacks generalizability and can lead to misleading directions that hinder progress (**Hall** *et al.*, 2018). Consequently, the Science of Team Science (SciTS), an interdisciplinary research area, has emerged, which uses experimental research methods to study how scientific teams are organized, how they communicate, and how they conduct research to provide evidence-based solutions for team collaboration.

Since the 21st century, the dramatic growth of publications in the SciTS field indicates that more and more scholars are interested in team science. However, some critical concepts of SciTS are still vague, and the overall development chain of SciTS has never been systematically reviewed. Therefore, in this paper, we use bibliometrics and information visualization methods to clarify the relevant connotations of team science and provide a systematic review of SciTS in terms of its emergence, development, and research progress. Our goal is to deepen researchers' understanding of team science and promote the further development of SciTS.

2. Relevant connotations of SciTS

2.1. Team

The concept of a team has a long history and has been defined by many scholars from several perspectives, with Stephen P. Robbins proposing the more popular view that a team is a formal group of individuals who depend on each other to achieve a goal (**Robbins**, 2004). This definition highlights the difference between a "team" and a "group", meaning that all teams are groups, but only formal groups can be teams. Other scholars have added to this concept. For example, Gary Hamel argued that team members are complementary and interdependent because they take on specific tasks and share responsibility for achieving team goals (**Hamel**, 2008).

In terms of types of teams, Rey-Rocha *et al.* define "team" from two perspectives. From the input perspective, teams are formed based on existing administrative arrangements, e.g., where colleagues belong to the same administrative unit (**Rey-Rocha** *et al.*, 2006). These are referred to as traditional teams. However, some researchers suggest removing the reference to administrative units from the definition of a team because if this constraint stays in place, many interdisciplinary teams would be excluded (**Liu** *et al.*, 2020). From the output perspective, teams are formed based on collaborative relationships, e.g., where coauthors work together on an article. These teams are referred to as virtual teams. Teams based on co-authorship have the advantage of verifiability, data availability, and ease of measurement. Hence, this is the most common way to study scientific collaboration. In addition, there is another type of team called a temporary team. These types of teams are formed at the start of a project and dissolved once the work is complete (**Goodman**; **Goodman**, 1976). By definition, a temporary team is a group of workers who are temporarily organized to work together in order to complete a complex task. Usually, the task is short-term.

> The Science of Team Science (SciTS) is a new field of interdisciplinary collaboration that uses experimental research methods to study how scientific teams are organized, communicate, and conduct to provide evidence-based solutions for team collaboration

Based on these existing concepts, we consider a team to be a formal group of individuals who complement their talents and depend on each other to achieve common goals, meet certain standards, and/or carry out responsibilities. There are three types of teams: traditional teams, virtual teams, and temporary teams.

2.2. Cross-disciplinary team

In the field of SciTS, teams are often created to solve complex, large-scale societal and environmental challenges (**Read** *et al.*, 2016), such as climate change, nuclear power safety, and bioengineering. Finding solutions to these 'wicked' problems requires research collaborations across disciplinary, organizational, and geographic boundaries (**Hall** *et al.*, 2018). Thus, "teams" in SciTS are generally cross-disciplinary, striving to integrate concepts, methods, and theories drawn from two or more fields to solve complex problems (**Falk-Krzesinski** *et al.*, 2011; **Stokols**; **Hall** *et al.*, 2008). Rosenfield conceptualizes four main types of cross-disciplinary collaboration teams, which depend on the complexity of the problem: unidisciplinary teams, multidisciplinary teams, interdisciplinary teams, and transdisciplinary teams.

In unidisciplinary teams, researchers from a single discipline try to solve a research problem jointly.

In multidisciplinary teams, researchers have a common research problem, but researchers from different disciplines work independently and usually only combine their results at the end. This type of research is not typically pathbreaking, but it reveals different aspects of a given problem and can lead to immediate, albeit possibly short-lived, solutions.

In interdisciplinary teams, researchers interact and work jointly to address a common research problem. Their research design combines concepts and methods from each of their respective fields. Knowledge from different disciplines is blended with each other to discover and draw meaningful conclusions.

In transdisciplinary teams, researchers work jointly to develop and use a shared conceptual framework that integrates and extends discipline-specific theories, concepts, and methods to create new models and approaches to addressing a common research problem.

Table 1 summarizes the definitions and distinctions between unidisciplinary, multidisciplinary, interdisciplinary, and transdisciplinary teams.

Table 1. Four types of cross-disciplinary teams

Categories	Definition	Examples
Unidisciplinary teams	Researchers from a single discipline work together to address a common problem.	Some chemists work together to study the composition, concentration, and proportion of alcohol.
Multidisciplinary teams	Researchers work in parallel or sequentially from a disciplinary-specific base to address a common problem.	A chemist, neurologist, and pharmacologist review the issues of alcohol composition and concentration, the effects of alcohol consumption on the brain, and the effects of alcohol consumption on mental status from the perspective of their respective fields.
Interdisciplinary teams	Researchers work jointly but still on a disciplinary-specific basis to address a common problem.	A chemist, neurologist, and pharmacologist combine concepts and methods from their respective fields in a collaborative study to examine the interrelationships between alcohol composition and concentration, brain chemistry, and the mental status changes caused by alcohol consumption.
Transdisciplinary teams	Researchers work jointly using shared conceptual frameworks drawing together disciplinary-specific theories, concepts, and approaches to address a common problem.	A chemist, neurologist, and pharmacologist conduct a collaborative study to discover the interrelationships between alcohol composition and concentration, changes in brain chemistry, and changes in mental status due to alcohol consumption. They then combine and extend the concepts and methods from their respective fields to develop new frameworks, theories, models, and applications.

Source: Adapted from **Rosenfield** (1992); **Stokols**; **Hall** *et al.* (2008).

2.3. Team science

Although team science itself and its content are not necessarily new, this new label it has been given and the increasing attention being paid to team science is an important recognition that the complexity of scientific challenges requires scientists to transcend disciplinary boundaries and begin working on problems together (**Fiore**, 2008). Health science is at the forefront of the team science field, and it has long been recognized that solving complex health problems not only requires multifaceted thinking but for other disciplines to play a significant role in solving the problems (**Fiore**, 2008). For this reason, team science is becoming the primary architecture for biomedical research and clinical studies addressing complex human health problems.

In fact, the *National Institutes of Health* (*NIH*) have developed their own definition of team science: Team science entails team members with expertise in different health fields working together to integrate their knowledge, skills, and perspectives into clinically focused research projects (*National Research Council*, *NRC*, 2015), the essence of which is the application of multidisciplinary concepts, methods, and theories to create new knowledge to solve complex health problems (**Little** *et al.*, 2017; *National Research Council*, *NRC*, 2015). This definition can be considered a gold standard for the definition of team science (**Baker**, 2015).

On the basis of this definition, the concept of team science has been extended and supplemented. In terms of team size, team science is a scientific collaboration conducted by more than one individual in an interdependent fashion (*National Research Council*, *NRC*, 2015). According to *Enhancing the effectiveness of Team Science*, "team science" is collaborative research conducted by small research teams (up to and including ten people) or large research teams (more than ten people) (*National Research Council*, *NRC*, 2015). In such collaborative research, new insights and solutions are developed by sharing information, resources, and expertise among team members to achieve common goals. This sharing occurs between individuals and administrative units, not only in one discipline but also between different disciplines (**Liu** *et al.*, 2020).

Little *et al.* (2017) point out that team science is a dimension of effective and impactful interprofessional collaborative research practice. Although it is possible for team science to be unidisciplinary, team science most often implies cross-disciplinarity with varying degrees of interaction and integration (**Fiore**, 2008; **Wagner** *et al.*, 2011). In addition, although team science has great prospects for promoting scientific progress, determining which approach is best for achieving the team's goals and maximizing the team's performance is often addressed by assembling leaders in the science community to discuss responses. Yet, the anecdotal evidence generated by such conversations lacks generalizability (**Hall** *et al.*, 2018). Therefore, empirical evidence and evidence-based solutions need to be built to fully realize the potential of team science (**Börner** *et al.*, 2010; **Fiore**, 2008; **Stokols**; **Misra** *et al.*, 2008). It is this need that has directly stimulated the emergence of the Science of Team Science(SciTS).

2.4. The Science of Team Science

The Science of Team Science (SciTS) is a new interdisciplinary field that focuses on the processes by which research teams organize, communicate, and conduct research (**Liu** *et al.*, 2020). An important goal for SciTS is to facilitate "smarter" science (**Stokols**; **Hall** *et al.*, 2008) by using empirical research methods to understand and manage the circumstances that facilitate or hinder the effectiveness of team science initiatives (*National Research Council*, *NRC*, 2015). As a branch of scientific study, SciTS is concerned with understanding, enhancing, and evaluating antecedent conditions, collaborative processes, and the outcomes associated with team science. Additionally, and importantly, the goal is to allow research findings to be translated into new scientific knowledge, practices, and policies (**Croyle**, 2008; **Little** *et al.*, 2017; **Stokols**, 2006; **Stokols**; **Hall** *et al.*, 2008; **Syme**, 2008). The philosophy is similar to virtual team theory, which is based on the "I-P-O model" (**Stokols**; **Misra** *et al.*, 2008). SciTS has two major research streams:

- to find internal and external factors that maximize the efficiency, productivity, and effectiveness of team science;
- to use the knowledge found to improve the effectiveness of collaboration.

Hence, SciTS includes both theoretical and empirical research (**Liu** *et al.*, 2020).

Team science and SciTS are different but related. Team science has given rise to SciTS, which seeks a meta-analysis or meta-understanding of team science (**Little** *et al.*, 2017). Team science focuses on solving particular problems, such as cancer, heart disease, community violence, environmental degradation, etc., through scientific collaborations from multiple disciplines or fields. SciTS, however, focuses on understanding and enhancing the antecedent conditions, collaborative processes, and outcomes associated with team science initiatives, including their scientific discoveries, educational outcomes, and research translations (**Croyle**, 2008; **Stokols**, 2006; **Syme**, 2008). In a word, SciTS contributes to understanding how teams work together to achieve scientific breakthroughs that cannot be realized through individual or simply additive efforts (**Falk-Krzesinski** *et al.*, 2011; **Liu** *et al.*, 2020). However, as with many new and developing fields, the exact delineation of SciTS is unclear, although scholars generally agree that SciTS focuses on understanding and enhancing the conditions, processes, and outcomes of team science (**Liu** *et al.*, 2020).

3. Emergence and development of SciTS

Although research on teams and collaboration has been undertaken for quite some time, the formal introduction of SciTS can be traced back to 2006, when the first conference on the subject was held. The prevailing view in the academic community is that this point marks the official emergence of SciTS. Notably, however, prior to that, some researchers were already contributing to team science. Figure 1 shows some of the key milestones in the SciTS field. Descriptions follow.

3.1. Emergence of SciTS

The scale and complexity of today's biomedical research problems increasingly require scientists to work outside their own disciplines. For example, solving the puzzle of complex diseases ranging from obesity to cancer requires a comprehensive understanding of the interplay between genetics, diet, infectious factors, environment, and behavior. This requires integrating the expertise of biological scientists, mathematicians, physical scientists, computer scientists, and others.

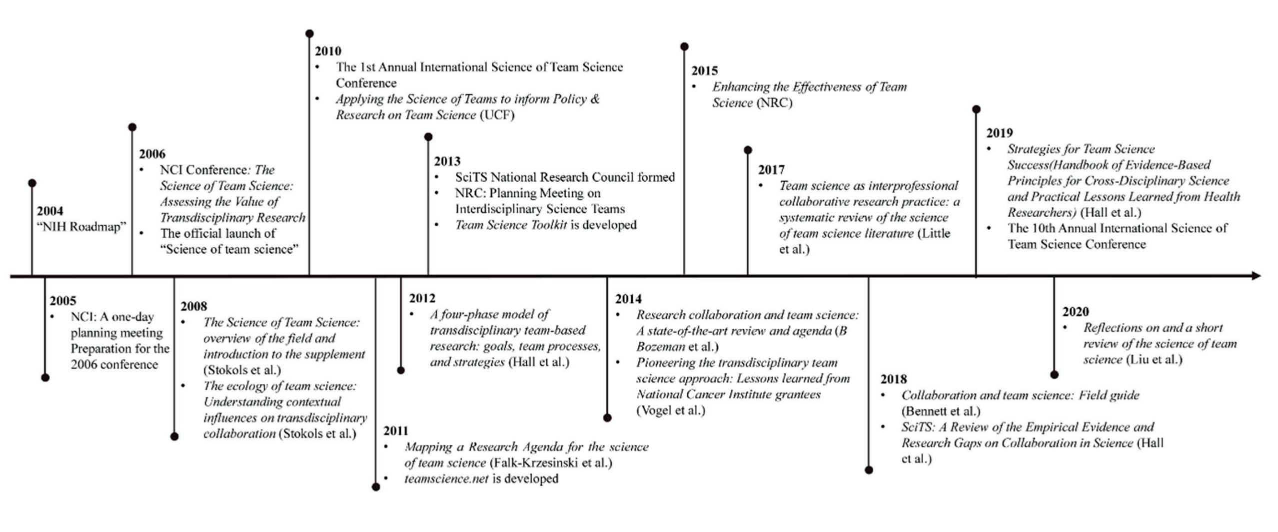

Figure 1. Key milestones in the SciTS field

After recognizing this difficulty, the *National Institutes of Health* (*NIH*) and its leadership in 2004 engaged in a process dubbed the "*NIH* Roadmap", which aimed to transform the way biomedical research was conducted. According to the roadmap, the *NIH* proposed to build teams that were different from traditional research teams. The idea was to improve health through collaborative efforts, including exploratory centers for interdisciplinary research and training for a new interdisciplinary research workforce. Most importantly, the *NIH* encouraged the exploration of new organizational models for team science, which can be seen as an informal instigator for the formal introduction of team science.

In 2005, the *National Cancer Institute* (*NCI*), a division of the *NIH*, invited many scholars in the SciTS field for a one-day planning meeting. The agenda included:

- evaluating the development status of SciTS;
- drafting an agenda of high-priority issues for future study;
- clarifying critical goals and strategies for the 2006 conference; and
- preparing a call for papers from scholars in the field (**Stokols**; **Hall** *et al.*, 2008).

This meeting can be seen as a prelude to the 2006 conference (*Annual International Science of Team Science*).

In October 2006, the *NCI* launched the *Annual International Science of Team Science Conference.* The conference had several aims: addressing ambiguities and gaps in the SciTS literature; promoting further integration of knowledge in the field; and identifying major questions for future study (**Little** *et al.*, 2017). The concept of SciTS was formally proposed for the first time at this conference, marking the official launch of this field. And ever since, SciTS researchers have been developing research agendas with the participation of experts (**Börner** *et al.*, 2010) and stakeholders (**Falk-Krzesinski** *et al.*, 2011), resulting in a wealth of relevant literature that has advanced the field (**Hall** *et al.*, 2018).

The emerging SciTS field was subsequently further developed when the *American Journal of Preventive Medicine* published a supplement based on the proceedings of the 2006 conference in July 2008. In this supplement, Stokols provided an overview of the major conceptual, methodologic, and translational concerns in the SciTS field (**Stokols**; **Hall** *et al.*, 2008). This paper effectively consolidated recent work in the field by assessing the various conceptual issues that must be addressed as a basis for launching future team science initiatives (**Hall**; **Feng** *et al.*, 2008).

3.2. Development of SciTS

3.2.1. *International Science of Team Science Conference*

To better understand how best to engage in team science to facilitate collaborative translational research and meet societal needs, the *First Annual International Science of Team Science Conference* was held in Chicago in April 2010, hosted by the *Research Team Support* (*RTS*) of the *Northwestern University Clinical and Translational Sciences* (*Nucats*) *Institute* (**Falk-Krzesinski** *et al.*, 2010). This event marked SciTS as a new branch of science with an independent research orientation. This conference was the first international, multi-institutional forum dedicated to the emerging empirical field of SciTS. It brought together more than 200 team science leaders and practitioners from multiple disciplines and provided a platform for team science researchers to share the latest evidence-based methods in team collaboration and transdisciplinary research (**Börner** *et al.*, 2010; **Falk-Krzesinski** *et al.*, 2010). Since its

> The concept of SciTS was formally proposed for the first time at the *Annual International Science of Team Science Conference* launched by *NCI* in October 2006, marking the official launch of this field

success in 2010, the conference has been held regularly for 13 consecutive years and has been funded by multiple different sponsors, including the *National Institutes of Health* (*NIH*) and *National Cancer Institute* (*NCI*), as well as leading health research institutions (e.g., *Pcori*, *Baxter*, the *Mayo Clinic*, *Kemin*), world-renowned publishers (e.g., *Elsevier*, *ProQuest*), intelligence information providers (e.g., *Thomson Reuters*), developers of team science tools and online platforms (e.g., *VIVO*, *ToolBox*, *Breezio*, *Trellis*), the world's leading universities (e.g., *The University of Chicago*, *Duke University*, *Northwestern University*, *University of Florida*, *University of Central Florida*, *University of California Irvine*, *Michigan State University*), and several prominent associations and foundations (e.g., *The Scientific Research Honor Society*, *Sigma XI*, *John Templeton Foundation*). In recent years, the SciTS conferences have also been funded by the *Army Research Office*. Hence, it is clear that SciTS has become an increasingly supported and recognized field, and its conferences are a nexus for interdisciplinary collaboration. Table 2 summarizes some key details of the previous SciTS conferences.

Table 2. Details of the previous SciTS conferences

Year	Number of conference committees	Host	Location	Partners/Sponsors
2010	11	*Nucats Institute*	Chicago, USA	*Northwestern University*; *NCRR*; *NCI*; *NICO*
2011	14	*Nucats Institute*	Chicago, USA	*NCRR*; *NCI*; *University of Chicago*; *Baxter*; *Elsevier*; *RefWorks*; *Kemin*; *Recombinant*; *Arete*; *VIVO*; *Wellspring Worldwide*
2012	13	*Nucats Institute*	Chicago, USA	*NCRR*; *NCI*; *University of Chicago*; *Baxter*; *Elsevier*; *ProQuest*; *Recombinant*; *Takeda*; *Symplectic*; *Thomson Reuters*; *VIVO*
2013	13	*Nucats Institute*	Evanston, USA	*Baxter*; *Elsevier*; *Sonic*; *NICO*; *ProQuest*; *VIVO*; *Thomson Reuters*; *Team Science Toolkit*; *InfoReady*; *Northwestern University*
2014	16	*VIVO/SciTS*	Austin, USA	*Symplectic*;*Digital Science*; *Thomson Reuters*; *Elsevier Research Intelligence*; *Frontiers*; *Plum Analytics*;*Academic Analytics*
2015	15	*National Institutes of Health*	Bethesda, USA	Missing information*
2016	12	*Mayo Clinic*	Phoenix, USA	*Arizona State University*; *Breezio*; *Elsevier*; *Mayo Clinic*; *Sodexo*; *AAAS Trellis*; *University of Central Florida*
2017	13	*University of Central Florida*	Orlando, USA	*University of Central Florida*; *Templeton Foundation*; *University of Florida*; *NIH*; *AAAS Trellis*; *University of Missouri*; *Westat*
2018	16	*University of Texas Medical Branch*	Galveston, USA	*University of Texas Medical Branch*; *University of Texas*; *Elsevier*; *University of Central Florida*; *Knowinnovation*; *University of Houston*; *Michigan State University*; *IPE*[2]
2019	15	*Michigan State University*	Lansing, USA	*Michigan State University*; *University of Central Florida*; *Public Health*; *University of Michigan*; *University of Texas Medical Branch*; *Michigan State University*; *GW Libraries*; *UCI*; *Create for STEM Institute*; *a2ru*; *Children's National Health System*; *Exaptive*; *University of California-Irvine*; *Mclaren*; *Pcori*; *SMEP*; *Toolbox*; *HyLighter*; *Elsevier*; *U.S. Army Research Office*
2020	19	*Duke University*	Virtual conference	*Duke University*; *UNC*; *SIGMA XI*; *U.S. Army Research Office*
2021	16	*Virginia Tech*	Virtual conference	*Virginia Tech*; *U.S. Army Research Office*
2022	19	*University of Central Florida*	Virtual conference	*Army Research Office*; *John Templeton Foundation*; *Ghuccts*; *University of Maryland*; *Renci*; *UCF SMST*; *University of Virginia*; *VIMS*; *University of Wisconsin-Madison*

*Note: Information on partners/sponsors for the 2015 conference is missing.

3.2.2. Academic teams and organizations

The development of team science has brought about scientific breakthroughs but also created many challenges that, if not addressed, may mean that researchers do not achieve their project goals. Thus, there is a critical need for evidence-based guidance to address these obstacles. Based on this, in 2013, the *National Science Foundation* (*NSF*) requested that the *National Research Council* (*NRC*) establish a *Committee on the Science of Team Science*. Consisting of 13 experts, the committee is dedicated to conducting a consensus study to discover the individual, organizational, and environmental factors that influence the effectiveness of scientific teams – factors like team composition, leadership, and management, institutional structures, funding, and policies.

In 2015, the committee launched a report at the *National Academies Press* titled *Enhancing the Effectiveness of Team Science*. The report is the result of an in-depth, evidence-based study to analyze what is currently known about the processes and outcomes of team science, under what circumstances investments in team-based research are most conducive to maximizing benefits, and in what projects investments are most likely to yield intellectually novel discoveries and significant improvements in social, environmental, and public health issues. The report covers factors that influence the effectiveness of team science at the individual- and team-levels, as well as at the institutional- and organizational-levels. Its findings provide evidence-based guidance for the challenges faced in developing team science. When examining how individual- and team-level factors relate to effectiveness, the committee drew heavily on diverse methodological and conceptual approaches from SciTS and social science fields. When examining how organizational- and institutional-level factors relate to team effectiveness, the committee conducted literature reviews and undertook case studies on science policy, team management, and other aspects in companies, universities, research institutes, and other institutions. Until this report, many research findings were too fragmented to help the field pool understand and apply the knowledge scattered across different research areas by team science practitioners. Thus, with this report, the committee made a very significant contribution to integrating and translating the sum knowledge of the field. Additionally, the report includes nine recommendations for the ongoing development of team science and possible directions for further research.

SciTS conference is becoming a representative conference for interdisciplinary collaboration, with more institutions or organizations supporting and recognizing it

The *International Network for the Science of Team Science* (*INSciTS*) is the membership organization for all stakeholders invested in team science. It is a forum for sharing the latest evidence for what works in team science and for collaborating with one another to advance the SciTS field. *INSciTS Special Interest Groups* (SIGs) are member-led groups that provide a "home away from home" for *INSciTS* members to connect and collaborate with one another who share common interests in the SciTS field. SIGs help to build communities around shared interests, and members of these SIGs collaborate throughout the year to advance research in key priority areas (*INSciTS*, 2022). The currently active SIGs are listed in Table 3.

Table 3. Active SIGs and their example topics

Active SIGs	Example topics
Fostering Team Science In Academia	Appointment, promotion, and tenure policies Institutional organization and structures (centers, cross-departmental), Funders' influence - funding mechanisms, policies, guidelines, requirements Publishing opportunities and challenges
Team Science Education & Training	Development and dissemination of training and educational resources Undergraduate, graduate, and early career training Professional development Team science competencies
Team Incubation and Acceleration	Developing incubator activities and spaces at academic institutions Stimulating creativity through incubator activities and spaces Sharing/designing/disseminating best practices to support scientific teams Creating evidence-based interventions for team science
Scientometrics and Data Analytics for Team Science	Scientometrics indicators of team outcomes and communications patterns Network analysis for scientific collaborations Mechanisms and evaluation criteria for authorship in scientific publications Measuring interdisciplinary/novelty/conventionality in collaborative research
Interdisciplinary Executive Scientists, Research Development Professionals, and I^2S (Integration and Implementation Sciences) *Specialists*	Developing the profession Professional development – effective best practices, tools, methods, etc. Evaluation Hiring, promotion, and tenure

3.2.3. Team science initiatives

The growing recognition that collaboration among scientists from different disciplines will foster solutions to complex scientific problems has spurred initiatives to train researchers to collaborate in cross-disciplinary teams (**Ho** *et al.*, 2021). There has been a surge of interest and investments in large-scale team science programs to realize the unprecedented opportunities this research paradigm poses. Both public institutions and private foundations have funded and launched a large number of team science initiatives specifically designed to develop collaborative and often cross-disciplinary approaches to address complex and particular phenomena (**Fiore**, 2008; **Okamoto** *et al.*, 2015; **Stokols**; **Hall** *et al.*, 2008; **Stokols** *et al.*, 2006). For example, the *NIH*'s *National Center for Research Resources* funded the *Clinical and Translational Science Awards* (*CTSA*) to encourage researchers across disciplines to form teams and turn experimental discoveries into treatments for clinical patients (**Börner** *et al.*, 2010). The *Centers for Population Health and Health Disparities* program (*CPHHD*) was established to address health inequities and health disparities by combining approaches from different disciplines (e.g., those in the physical, biological, social, and behavioral sciences), analyzing their causes, and formulating appropriate interventions and policies (*National Institutes of Health*, *NIH*, 2010; **Okamoto** *et al.*, 2015). In mobile health, the *NIH*-supported annual *mHealth Training Institutes* (*mHTI*) has commenced an immersive training program intended to cultivate scientists who can engage in and lead interdisciplinary collaborations dedicated to finding effective mobile health (*mHealth*) solutions to complex healthcare problems (**Ho** *et al.*, 2021). Another initiative, the *Advancing Geriatrics Infrastructure and Network Growth* (*Aging*) *Initiative*, was funded by the *National Institute on Aging* in 2014 for a period of 3 years to develop team science infrastructure to advance research on multiple chronic conditions (MCC)

(**Garg** *et al.*, 2018). In cancer research, the *Transdisciplinary Research on Energetics and Cancer* (*TREC*) was established and funded by the *National Cancer Institute* (*NCI*) from 2005 to 2016. This was an interdisciplinary collaborative center looking at energy balance and cancer, whose mission was to study the relationships between obesity, nutrition, physical activity, and cancer. *TREC* integrated interdisciplinary knowledge from the social, behavioral, clinical, and basic sciences and proposed and implemented new interventions to reduce the burden of these diseases (**Hohl** *et al.*, 2021; **Patterson** *et al.*, 2013).

3.2.4. Supporting tools

Conducting team science presents important challenges for investigators that are sometimes more complex than in traditional single-investigator studies. For example, information and resources on the availability and reliability of team science, scientific collaboration, and cross-disciplinary research have been rare in the past. In addition, data sharing, communication, team leadership, and conflict resolution can all be difficult issues to navigate even for seasoned investigators. Moreover, traditional research tools and technologies often barely meet all the needs of today's research. As a result, researchers are developing and using more powerful web-based support tools to help conduct their research. Some of the more commonly used and representative tools include *Team science toolkit*, *Toolbox project*, *Teamscience.net*, *Research toolkit*, *VIVO*, and *Science of Science* (*Sci2*). These are summarized below.

Team Science Toolkit

Developed by the *National Cancer Institute* (*NCI*), the Team Science Toolkit is an interactive website that contains plenty of resources and information on team science practices and research to help users support, conduct and study team-based research. The purpose of the toolkit is to integrate cross-disciplinary knowledge, share experiences, and prevent any unnecessary duplication of effort. In addition, it provides a forum for sharing knowledge and practical experiences that are proving to play an important role in improving the effectiveness and efficacy of team science programs (**Vogel** *et al.*, 2013).

Toolbox Project

Supported by the *National Science Foundation* (*NSF*), the *Toolbox Project* is a training intervention designed to facilitate cross-disciplinary communication in science teams and groups. It provides a philosophical yet practical enhancement to cross-disciplinary, collaborative science. Specifically, the *Toolbox Project* systematically uses philosophy to help collaborators abstract away from their specific disciplinary differences and instead move toward conceptual common ground. It encourages collaborative teams to use philosophical approaches to enhance their conceptual understandings, and thereby foster the mutual understanding necessary for cross-disciplinary research. Through these themes, teams are enabled to meet project challenges more effectively (**Eigenbrode** *et al.*, 2007; **O'Rourke**; **Crowley**, 2013).

Teamscience.net

Supported by the *NIH* and developed by the *Northwestern University Center for Applied and Translational Sciences Institute*, *Teamscience.net* is a suite of e-learning resources that provides examples of real-life scenarios unique to team-based research (*Teamscience.net*, 2022). The purpose of *Teamscience.net* is to enhance skills for participating in or leading interdisciplinary and transdisciplinary science teams or groups. Within this web-based tool, there is a project named *Coalesce*, whose main goal is to build, evaluate and share up-to-date and easy-to-read resources online to facilitate learning and skill development in team science (**Aronoff**; **Bartkowiak**, 2012; **Yu** *et al.*, 2019).

VIVO

Supported by *NIH*, *VIVO* is a free, open-source web application that helps researchers search for other researchers by publication, research area, and teaching or professional affiliations across institutional boundaries (**Börner** *et al.*, 2012). For example, *My Dream Team Assembler*, which was developed and built by the *Sonic Research Group* at *Northwestern University* in close collaboration with the *Atlas Lab* of *Northwestern University*, is based on *VIVO.* The program recommends potential scientific collaborators and helps to form teams.

In addition, the *Researcher Toolkit* is an open-access web-based tool that provides resources to make research involving interdisciplinary collaborators easier. *Science of Science (Sci2)* is a tool for research and practice in the science of science. It supports temporal, geospatial, topical, network analysis and the visualization of scholarly datasets.

4. Research progress of SciTS

4.1. Data sources

From the previous section, we can see that SciTS is growing in an orderly and steady fashion. In this section, we hope to reveal some of the progress made by SciTS researchers by analyzing the characteristics of the literature and the research topics covered in the field. Our first step was to collect all SciTS publications indexed by the *Web of Science* (*WoS*) *Core Collection* (*Science Citation Index Expanded*, *Social Sciences Citation Index*, *Arts & Humanities Citation Index*) through the following data retrieval strategy:

TS = ("team science") AND PY=2005-2022

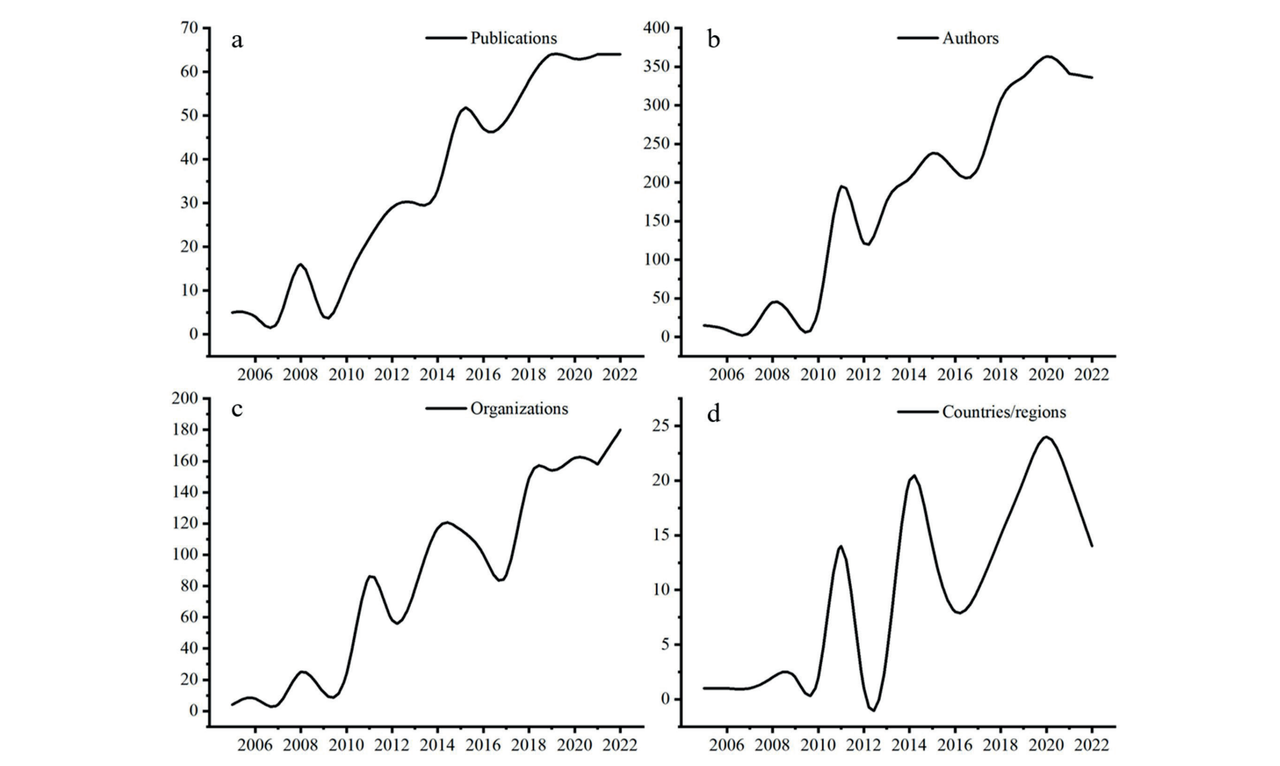

Figure 2. Distribution characteristics of SciTS publications

Selecting core lexical queries was essential for developing our search strategy (**Huang** *et al.*, 2015). Ultimately, we opted to only use "team science" as the core term to maximize the number of potentially relevant studies found. This met our objective of retrieving a comprehensive representation of publications on SciTS. Additionally, 2005 was chosen as the starting year because the first call for SciTS papers came out of the 2005 planning meeting. These studies are important and valuable as they represent the beginnings of team science research.

This search, conducted on November 3rd, 2022, resulted in 618 research publications. After a detailed data-cleaning process with *VantagePoint*, a powerful text-mining tool for discovering knowledge from literature databases, we arrived at our final dataset, which was used for further analysis.

4.2. Characteristics of the literature

The number of SciTS articles published per year is shown in Figure 2a. As team science has developed, total publications have increased, indicating that team science has become increasingly prevalent. Figures 2b, 2c, and 2d, respectively, show how SciTS has developed in terms of micro-level authors, meso-level organizations, and macro-level countries. We see that the number of authors, organizations, and countries/regions involved in team science research has generally risen, indicating that team science research is receiving more attention. Indirectly, these results reflect that the field has important research value. The United States has contributed significantly to the development of team science. For most years, the US accounts for a very high share of publications, typically exceeding 60%. Particularly in the first few years of SciTS's emergence, the US's participation rate was close to 100%. However, in more recent years, the discipline has started to spread to other countries, and the proportion of US articles has slightly declined. That said, the US's dominance over the field remains unquestionable.

4.3. The trend of interdisciplinary integration

SciTS is an emerging interdisciplinary field whose development is inseparable from the cross-integration of methods, tools, and knowledge in multiple disciplines. Therefore, to understand the disciplinary distribution and the dynamics of interdisciplinary integration in the field, we turned to *Science Overlay Mapping* (**Carley** *et al.*, 2017; **Ràfols** *et al.*, 2010). Science overlay mapping is a method of visualizing the relationships between disciplines within a field. As shown in Figure 3, the nodes represent *Web of Science* categories, the size of the node represents the number of publications, and nodes of the same color indicate that the categories belong to the same disciplinary cluster.

Combining Figure 3a with Figure 3b, we can see that SciTS publications mainly span Public Environmental Occupational Health, Medicine Research Experimental, Oncology, Medicine General Internal, and Health Care Sciences Services. All these disciplines are related to medicine, which is closely related to the fact that team science has its origins in the field of health sciences. In addition to the-

> The SciTS field is receiving more attention, with significant contributions from U.S. scholars

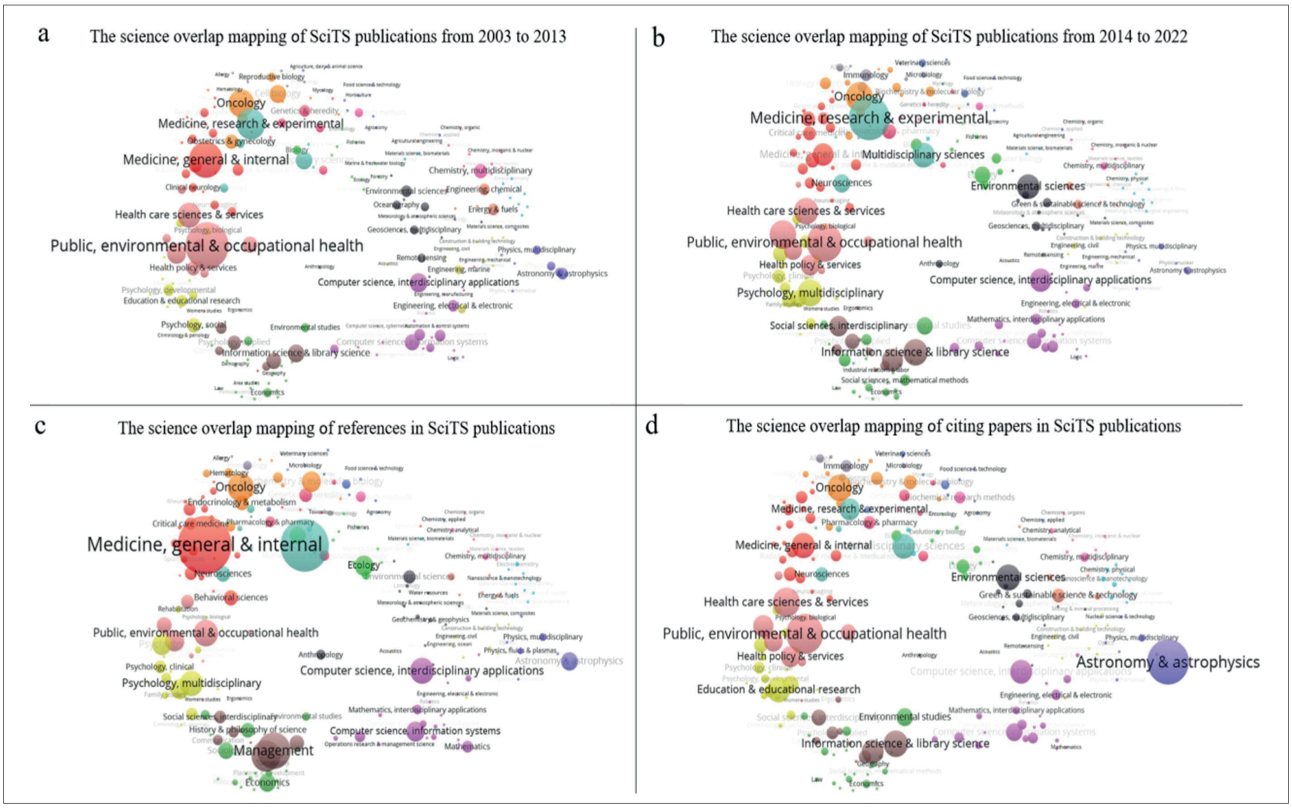

Figure 3. Science overlay maps based on SciTS publications

se medical disciplines, SciTS publications are also found in Information Science, Library Science, Psychology, Computer Science, Interdisciplinary Applications, and Management, etc. This shows that these disciplines are also discussing team science and interdisciplinary research. In terms of SciTS's temporal evolution, more disciplines were involved in the field in 2014-2022 than in 2005-2013. Hence, the reach of the field is growing. This observation also indicates that the interdisciplinary characteristics of team science are becoming more prominent, and the trends in interdisciplinary integration are becoming more obvious.

From the perspective of references, we can see which disciplines have played a key role in supporting the development of SciTS. From the perspective of citing papers, we can see which disciplinary problems SciTS is trying to solve by integrating interdisciplinary knowledge. The SciTS publications we retrieved included a total of 22,971 references as well as 10,246 citing papers. Science overlay maps for the references and the citing papers are shown in Figures 3c and 3d, respectively.

Comparing Figure 3c with Figure 3d, we can see that there are certain differences between the knowledge inputs and knowledge outputs of SciTS. In terms of knowledge inputs, the rise of SciTS has mainly been off the back of disciplines such as Medicine (General Internal), Multidisciplinary Science, Management, Business, Oncology, Public Environmental Occupational Health, Computer Science Interdisciplinary Applications, and Psychology Multidisciplinary (see Figure 3c). These disciplines have provided the knowledge, experience, methods, and tools for teamwork and interdisciplinary research. In terms of knowledge outputs, the research results from SciTS have been mostly digested by the disciplines of Astronomy Astrophysics, Public Environmental Occupational Health, Health Care Sciences Services, Oncology, Information Science Library Science, Environmental Sciences, Education & Educational Research and Medicine General Internal (see Figure 3d). In summary, team science has mainly combined the theories, perspectives, tools, and methods from Medicine (General Internal), Multidisciplinary science, Management, Business, and other disciplines to address the major research problems involved and faced by Astronomy Astrophysics, Public Environmental Occupational Health, and Health Care Sciences Services, among others.

4.4. Research topics

The clustering analysis of author keywords reveals the research themes that SciTS researchers have focused on. The data cleaning and processing protocol included: (1) removing meaningless words, such as trends, issues, globe, goals, etc.; (2) merging subject terms with the same meaning, such as singular and plural words, keywords with a switched word order but the same connotation, synonyms or near-synonyms, full names and abbreviations, etc.; and (3) removing three high-frequency keywords, being "team science", "SciTS" and "the science of team science", along with keywords with a frequency of less than 2. After clustering based on the Leiden algorithm (**Traag** *et al.*, 2019), we built a topic cluster map of the field, which is shown in Figure 4. As illustrated, the field comprises seven main clusters of research.

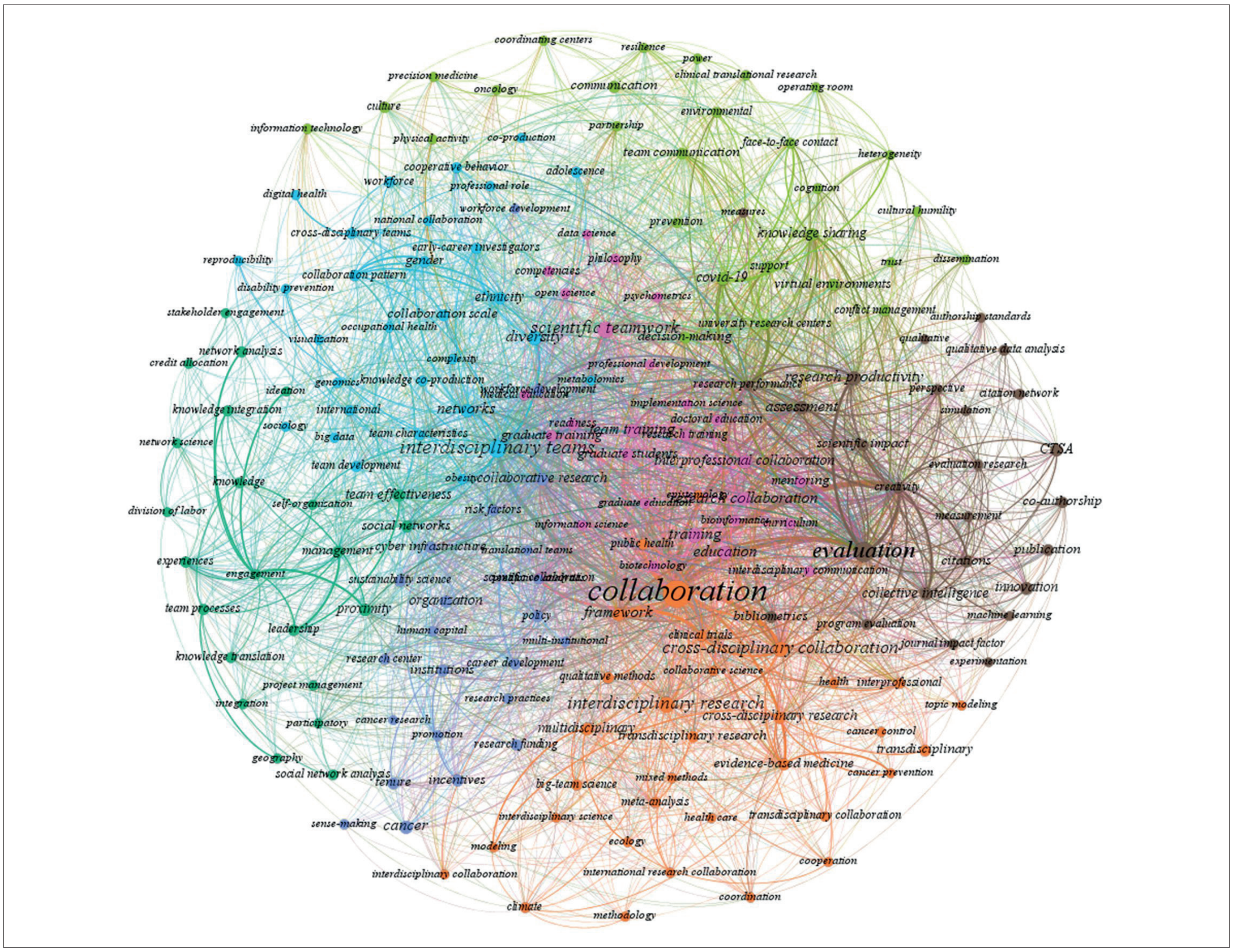

Figure 4. The topic clustering map of the SciTS publications

4.4.1. The definition and theory of the Science of Team Science

The orange nodes in Figure 4 form a cluster that contains some relatively large nodes, such as collaboration, cross-disciplinary collaboration, interdisciplinary research, framework, evidence-based medicine, transdisciplinary, qualitative methods, and meta-analysis. These are the most basic attributes of SciTS itself.

In this cluster, the contemporary science community has adopted a problem-driven approach to knowledge production, which tends to blur the boundaries between disciplines. Further, as **Milojević** (2014) reports, knowledge permeability has become increasingly evident, leading to the emergence of cross-disciplinarity. It is also suggested that team science would benefit from further developing interdisciplinary research in its quest to address complex research questions. Additionally, the development of evidence-based practices and policies should be promoted by integrating methods and theories from multiple disciplines (**Hall** *et al.*, 2018).

In terms of the theoretical development of SciTS, M. Little concludes that team science is a dimension of interprofessional collaborative practice that allows professionals or practitioners from multiple disciplines to collaborate by leveraging different perspectives and knowledge (**Little** *et al.*, 2017). W. Bedwell argues that cross-disciplinary collaboration is an integrated, multi-level concept that requires an overall view of collaboration (**Bedwell** *et al.*, 2012). Indeed, collaboration is essentially a back-and-forth process that requires each party involved to actively contribute in some way across the lifecycle of collaborative effort (**Bedwell** *et al.*, 2012). D. Stokols highlights the important roles of systems theory and systems thinking in helping SciTS to develop, such as the ability to reveal the interdependencies among systemic units that operate at these different levels (**Stokols**; **Hall** *et al.*, 2008), but which has been largely neglected (**Morrison**, 2008; **Provan** *et al.*, 2008). On the other hand, Pedro J. Ramos-Villagrasa *et al.* use a systematic review to present a view of teams as complex adaptive systems, which allows for a better understanding of teams and team science (**Ramos-Villagrasa** *et al.*, 2018).

In terms of the models and frameworks used in SciTS, the *Wisconsin Interventions for Team Science* (*WITS*) is a dynamic framework whose primary goal is to evaluate the effectiveness of translational team interventions so that evaluation results can be used to support subsequent team science programs (**Rolland** *et al.*, 2021). As another example, K. Hall and J. Holmes present multistage conceptual frameworks that have been used to guide transdisciplinary research, training, and community intervention efforts within initiatives undertaken by the *NCI Cphhd* and *TREC* (**Hall**; **Stokols** *et al.*, 2008; **Holmes** *et al.*, 2008). From the perspective of the collaboration process, **Tuckman** (1965) proposes a five-stage team development model that is considered to be the basic foundation of the team development model:

- the forming stage;
- the storming stage;
- the norming stage;
- the performing stage; and
- the adjourning stage.

> Investments in team science initiatives need to be strategic and should be reserved for those research topics that are best suited to and would benefit most from interdisciplinary collaborative approaches

In addition, some scholars have put forward an antecedent-process-outcome model in which the antecedent and process variables specified in the model influence several near-, mid-, and long-term outcomes of scientific collaboration (**Stokols** *et al.*, 2003). Similarly, other scholars have developed an input-process-output model that can be used to identify and describe the characteristics and effectiveness of cross-disciplinary integration (**Bugin** *et al.*, 2021).

In conclusion, many studies in SciTS discuss team science issues by introducing theoretical models and conceptual frameworks from other fields to add a more intuitive understanding of team science. Some examples of the theoretical models used to describe interdisciplinary team science include the social-ecologic model (**Stokols** *et al.*, 2005), systems thinking and complexity theory (**Shen**, 2008), network analysis (**Nash**, 2008), the social-determinants paradigm (**Morgan** *et al.*, 2003), paradox theory, and more. These theories and models are drawn from such diverse disciplines as sociology, ecology, physics, and biology, with a primary focus on understanding the factors that facilitate or hinder the development of team science (**Hall**; **Feng** *et al.*, 2008).

4.4.2. Team composition and collaboration patterns

The cluster of blue nodes in Figure 4 features interdisciplinary teams, diversity, networks, collaboration patterns, ethnicity, team development, collaboration scale, gender, and early-career investigators. These nodes mainly reveal the constituent elements of teams and the collaboration patterns shaped by the attributes of the team members.

Research teams are always organized around a purpose that is accompanied by a desire to achieve certain goals and improve upon past research performance. Team composition is an important aspect of this paradigm. It involves a team's structure, its collaboration patterns, how its affective states are shaped, the behavioral processes at work, and the cognitive states that ultimately affect how teams achieve their goals (i.e., the ABCs of teamwork) (**Bell** *et al.*, 2018).

Team composition has two connotations. For a start, team composition refers to the team members' attributes, such as age, gender, country, university, sector, ethnicity, mother tongue, interdisciplinarity, academic rank, and professional role, as well as the cultural context within which members were brought up and received training, as shown in Table 9. Additionally, the attributes of the team, such as its size, diversity, spirit, leadership, and levels of inclusion, are equally important factors in team composition, as shown in Table 4. All of the above largely influences the effectiveness of teamwork (**Liu** *et al.*, 2020).

Table 4. Some elements of team composition

Elements	**Description**
Age	Younger *versus* older researchers
Gender	All-female, all-male, mixed
Country	National or international
University	Same university or more than one university
Sector	Same-sector or multi-sectorial
Ethnic	The relationship between ethnic belonging and group identification
Mother tongue	Members speaking the same language or different languages
Interdisciplinarity	Unidisciplinarity or cross-disciplinarity
Academic rank	From doctoral students to full professors (in university teams)
Leadership	The relationship between leader characteristics and team effectiveness
Team size	Number of team members
Team diversity	Levels of difference in team member attributes
Team spirit	Whether teams have a sense of belonging, honor, and cohesion
Team inclusion	Acceptance of differences and promotion of trust among members

Source: Adapted from **Liu** *et al.* (2020).

Scholars often use empirical research methods to argue over which characteristics of team science and which team compositions are the most conducive to achieving goals or improving performance. For example, studies on the gender of team members have found that heterosexual collaboration tends to lead to better outcomes than same-sex collaboration (**Campbell** *et al.*, 2013). In terms of academic rank, the team's results tend to have a greater citation impact when the team includes at least one full professor (**Bales** *et al.*, 2014) or a more senior first author (**Stvilia** *et al.*, 2011). When it comes to team size, some studies have shown that larger teams are often more productive (**Jeong**; **Choi**, 2015) and impactful (**Sud**; **Thelwall**, 2016), while others have found that small teams are more likely to generate new disruptive ideas (**Wu** *et al.*, 2019). Studies on diversity have shown that high levels of diversity have certain advantages (**Guan** *et al.*, 2015). However, too much diversity can lead to fragmentation and inefficiencies. There are too many relevant research findings to list them all, but, in general, it is clear that team composition is directly related to the effectiveness of collaboration and how the team performs.

> Seven main streams of research in SciTS field, which are: the definition and theory of SciTS, team composition and collaboration pattern, team formation and team functioning, physical environment and culture of teams, institution and organization for teams, training and education of interdisciplinary collaboration, and the measurement and evaluation of team science

4.4.3. Team formation and team functioning

The dark green cluster in Figure 4 contains nodes such as team processes, team effectiveness, knowledge integration, management, social networks, leadership, proximity, experiences, engagement, and knowledge translation. These themes primarily pertain to team formation and team functioning. The former is focused on "who should be part of a team and how to find them", while the latter is focused on "what strategies should be used to improve team functioning".

Team formation is different from team composition. Team composition focuses on which factors help teams achieve their goals and/or improve team performance, while team formation is primarily concerned with how to form a team of researchers with different areas of expertise to solve a particular research problem at a minimal cost.

The issue of team formation has been studied for some time. M. Büyükboyaci finds that letting workers voluntarily join teams can help to form skill-complementary teams where each worker is able to focus on the task they do best. Moreover, such endogenous team formation can positively impact overall productivity (**Büyükboyaci**; **Robbett**, 2019). In addition to self-organization, the process of team formation can also be seen as an NP-hard problem (non-deterministic polynomial-time hardness), which is to find workers who can contribute their efforts and accomplish a specific task at the lowest cost. Thus, the methods applied to NP-hard or NP-complete problems may be strong applications of team formation (**Yu** *et al.*, 2019). At present, heuristic approaches have already been used to solve the issue of team formation. For example, Fitzpatrick and Askin designed a heuristic solution for forming maximally effective teams that consider innate tendencies, interpersonal skills, and technical skills (**Fitzpatrick**; **Askin**, 2005). Another example is the simulated annealing algorithm developed by Baykasoglu, which solves a fuzzy optimization model. It selects the right team members for a project who should together be able to perform a particular task within a given deadline (**Baykasoglu** *et al.*, 2007).

Team formation is influenced by many factors, including physical proximity, social ties, brokers, and prior experience with collaboration (**Hall** *et al.*, 2018). Among these, physical proximity increases the likelihood of forming new collaborations and obtaining funding (**Binz-Scharf** *et al.*, 2015). For example, researchers located within the same department or institution are more likely to form collaboration teams (**Kabo** *et al.*, 2014). In addition to physical proximity, social ties are a crucial factor in team formation. A. Smith and J. Wang argue that weak social ties contribute to team formation, but the balance between weak and strong social ties is more important for team development (**Smith** *et al.*, 2016; **Wang**, 2016). Furthermore, in social relationships, brokers can act as intermediaries between researchers, linking otherwise isolated individuals to form new collaborations (**Murthy**; **Lewis**, 2015). From collaboration experience, researchers tend to collaborate with past collaborators (**Lungeanu**; **Contractor**, 2015) or choose partners with a pleasant collaboration history to continue working together. However, a recent study found that fresh teams have higher originality and a more-diverse impact compared to older teams (**Zeng** *et al.*, 2021).

After a team has been formed, the critical issue is what strategies should be used to ensure the team works effectively, which is exactly what team functioning considers. Team functioning is the process by which team members work together to achieve a common goal. In other words, team functioning is the process of transforming team inputs into team outputs, such as team effectiveness, collaboration efficiency, satisfaction, etc.

Effective team functioning relies on the right management style, which includes effective leadership behaviors, a positive and enjoyable collaborative environment, and other such factors. Early studies on teams suggest that leadership substantially influences collaborative processes and outcomes (**Morgan** *et al.*, 2003; **Stokols**, 2006). Effective leaders are skilled at generating and maintaining trust, fostering shared dreams among members, and providing them with direction, meaning, and hope. At present, there is a strong call for "transformational leaders", which refers to leaders who are able to communicate a shared vision and maximize the potential of their team members through intellectual stimulation and personalized care to achieve the highest levels of team performance (**Li** *et al.*, 2017).

> It is necessary to inspire scholars from more countries to participate in the SciTS research to bolster underrepresented groups in team science, thereby building a multicultural and multi-stakeholder subject area

Members of interdisciplinary teams are often heterogeneous. So, to achieve effective team functioning, leaders need to know how to manage and embrace differences (**Bennett**; **Gadlin**, 2012). When managed properly, the diversity of a team can be a powerful resource, as different knowledge and perspectives can be integrated to solve problems (**Mannix**; **Neale**, 2005). Meanwhile, trust plays a crucial role in team functioning and collaboration effectiveness. Research has shown that trusting relationships in teams facilitate knowledge sharing and, thus, the achievement of team goals (**Mutahar** *et al.*, 2022). Conversely, when there are conflicts in a team, knowledge-sharing behaviors are reduced (**Xia**; **Ya**, 2012). Although conflict is inevitable in team functioning, its impact can be greatly minimized by managing and anticipating (**Bennett**; **Gadlin**, 2012). For example, accurate decision-making and good communication can effectively mitigate team conflicts, thereby enhancing mutual understanding and facilitating the inclusion of diverse ideas (**McGreavy** *et al.*, 2015).

In addition, the process of team functioning includes three team states: namely, affective, behavioral, and cognitive processes (**Hall** *et al.*, 2018; **Liu** *et al.*, 2020). In terms of affective states, a good affective state between team members will reduce the possibility of friction and discord and enhance team cohesion. U. Ghuman demonstrates that team performance improves and learning capacity increases if the team can develop emotional awareness and hence positively manage the emotional relationships at play within the team (**Ghuman**, 2016). In terms of behavioral states, face-to-face communication is a more effective communication medium than virtual forms, such as video conferencing (**Jeong**; **Choi**, 2015). In addition, the right collaboration behaviors are crucial in team science, including the division of responsibilities for tasks, knowledge transfer among researchers, the development of training programs, etc. (**Cummings**; **Kiesler**, 2007). In terms of cognition states, it has been shown that there is a strong relationship between team cognition and team performance (**Fernández** *et al.*, 2017). A key feature of improving interdisciplinary team performance is the development of shared mental models among team members (**Hall** *et al.*, 2018). When there is some synchronization between the team's overall goals and the team members' aspirations and career needs, that team tends to function more smoothly and efficiently (**Zucker**, 2012).

4.4.4. Physical environment and culture of teams

The predominant topics in the light green cluster in Figure 4 include knowledge sharing, culture, support, virtual environments, face-to-face contact, trust, team communication, decision-making, and conflict management. These keywords all relate to one's physical environment and cultural factors influencing interdisciplinary team collaboration.

The physical environment in teamwork refers to work-related infrastructure. Early studies of team environments, such as **Sundstrom** *et al.* (1990), demonstrate the importance of physical environments for team development, such as opportunities for face-to-face contact, comfortable meeting areas, distraction-free office and laboratory settings, private workspaces, and shared team spaces.

Technology-mediated collaboration has changed the way people interact with their socio-physical environments. Interdisciplinary collaborative research is no longer limited to the same institution or country. In international collaborations, working across multiple time zones means that team members are in different stages of their circadian rhythms. These time differences can mean that team members are not always in the best working condition when they collaborate. Also, remote collaboration makes it difficult to grasp the mental and emotional state of partners. As a result, remote collaborations may suffer from poor coordination and reduced efficiency. By contrast, physical proximity, which also implies there is no time difference between collaborators, can generate more frequent contact and prompt informal communication, which is important for a good collaboration (**Stokols**; **Misra** *et al.*, 2008). Face-to-face contact, in particular, can increase the frequency and efficiency of information exchanges and promote the transfer of knowledge, especially tacit knowledge (**Knoben**; **Oerlemans**, 2006). This is because team science projects spend a substantial amount of time in group meetings and brainstorming sessions. Therefore, in addition to the conditions for face-to-face communication, there is also a need for an environment that meets a variety of office needs, such as comfortable meeting spaces for teams to conduct group discussions and brainstorming along side private, distraction-free workspaces. Some studies have already pointed out whether the team members like their physical environment positively correlates to their levels of cross-disciplinary collaboration (**Stokols**; **Misra** *et al.*, 2008).

Team culture is also an important measure in team environments. Culture is defined as shared cognitive structures and consensus around culturally correct values, attitudes, and normative behaviors (**Strekalova**, 2022). A team-friendly environment requires a team culture of integrity, trust, respect, and sharing from the top down. Leadership plays a key role in the formation and development of team culture. Thus, studies on how leadership can foster a team culture are important works of research in the SciTS field. Studies on how team cultures can address differences in discipline, gender, race, and other background attribute to maintain cohesion and productivity are particularly valuable (**Lee**; **Jabloner**, 2017). Furthermore, in terms of conflict culture in teams, good scientific teams need good conflicts. In team science, one must recognize the danger of artificial harmony, which refers to team members acting as if they get along well in an environment where serious problems are not being addressed. Instead, the right team culture is one that empowers teammates to express their opinions, leading to healthy disagreements and debates. Therefore, teams must master the art of identifying and realizing the best level of conflict for them to achieve optimal team performance (**Sen**, 2021).

4.4.5. Institution and organization for teams

The purple cluster in Figure 4 assembles the themes related to cyberinfrastructure, organization, sustainability science, institutions, research funding, policy, workforce development, incentives, tenure and promotion, and similar. These themes concern the institutional and organizational factors that affect collaboration in interdisciplinary teams, such as nonhierarchical organization structures, strong organizational incentives, an inclusive and shared organizational climate, and diverse organizational activities.

Different opinions exist about the ideal organizational structure to support successful collaborations between professionals from a wide variety of disciplines. However, the traditional hierarchical pyramid still dominates. Rigidly structured organizations that are managed from the "top-down" often fail to provide an optimum environment for self-motivation, creativity, and engagement –all of which are important requirements for effective collaboration (**Cross** *et al.*, 2011; **Hardin** *et al.*, 2017; **Swensen** *et al.*, 2016). The other type is a nonhierarchical organization structure. This refers to a collaboration in a culture of equality and is a structure that recognizes each individual team member's specific and complementary skills. It considers that people have common and aligned interests, which can provide the basis for transparent, fair, and productive collaborations. In this organizational structure, team members have a certain autonomy to participate in goal-setting and decision-making, which is considered an effective means of advancing efficiency and innovation (**Eekhoff** *et al.*, 2020). Since team science activities are often oriented toward important projects that require high levels of collaborative efficiency, as well as innovation, a nonhierarchic organizational structure may be more appropriate.

In terms of incentives, a strong organizational incentive is a prerequisite for sustaining motivation among participants in team science initiatives. Incentives also facilitate participation and help sustain collaborations. Broad-based institutional support for team science initiatives and rewards for collaborative research can increase the willingness of researchers to collaborate. For example, one could change university tenure and promotion policies to give more recognition and rewards to those who engage in team science initiatives (**Rhoten**; **Parker**, 2004; **Stokols**, 2006). Further, support from funding institutions is critical to achieving the potential value-adds from interdisciplinarity, especially when attempting to mount large-scale interdisciplinary initiatives (**Lyall** *et al.*, 2013). Likewise, long-term funding is essential for building sustainable partnerships between coalition members (**Stokols**, 2006).

An inclusive and sharing organizational climate is a catalyst for interdisciplinary collaboration. Team science requires the integration of multiple disciplinary perspectives to better understand and ameliorate big problems. Therefore, the breadth of disciplinary perspectives represented within the collaborative team or organization is critical to teamwork. It has been shown that working groups that welcome diverse opinions and adopt a worldview tend to communicate more. They are also more likely to include knowledge-bridging collaborators, which supports cross-disciplinary team performance (**Crowston** *et al.*, 2015). Additionally, building a shared organizational climate, where information, credit, and decision-making responsibilities are shared, is to be encouraged, as organizations and teams that lack a culture of sharing are likely to resist change and remain ineffective (**Stokols**; **Misra** *et al.*, 2008).

In an interdisciplinary collaboration, it is important for team members to be able to engage in frequent social gatherings, retreats, and other forms of face-to-face communication. Some studies have noted that face-to-face contact prior to engaging in remote collaboration is critical to establishing some degree of trust at the beginning of a program (**Olson**; **Olson**, 2000). Therefore, it is essential for teams, especially for teams that frequently use telecommuting, to organize diverse activities to increase trust and group identity among members.

4.4.6. Training and education of interdisciplinary collaboration

The magenta cluster in Figure 4 contains keywords such as scientific teamwork, interprofessional collaboration, training, education, team training, research collaboration, mentoring, and readiness. These keywords speak to the training and education factors affecting collaboration in interdisciplinary teams.

Training and educating researchers in SciTS is widely recognized as one of the most effective ways to enhance teamwork skills and team effectiveness. It is also thought to be an important driver for developing SciTS as a field. Training and education in team science can ensure researchers have the knowledge and competencies necessary for successful collaborations and may be particularly helpful in addressing two particular challenges in team science –highly diverse team members and high task interdependence. Conceptually, team training is defined as an intervention to improve team performance by teaching the competencies necessary for effective performance as a team (**Delise** *et al.*, 2010). Interdisciplinary and transdisciplinary education refers to long-term courses to prepare a generation of scholars to solve complex problems in interdisciplinary research environments (*National Research Council*, *NRC*, 2015). Training and education are interwoven, and both aim to prepare for team science.

Researchers have proposed a variety of team science competencies as important learning goals in training and education:

- team knowledge, such as task understanding, shared mental models, and role knowledge;
- team skills, such as communication, assertiveness, and situation assessment;
- team attitudes, such as team orientation, trust, and cohesion (*National Research Council*, *NRC*, 2015).

There are several representative strategies for teaching these three team competencies of knowledge, skills, and attitudes. These include cross-training, team self-correction training, knowledge development training, team coordination training, and team building.

(1) Cross-training is considered to be an effective means of training "interpositional knowledge" (IPK), which can help members of scientific teams develop both knowledges of the roles and competencies of different team members and also the common goals and shared expectations of teams.

(2) Team self-correction training refers to team members being empowered to improve their performance by reflecting on past performance events and self-diagnosing areas for improvement (**Smith-Jentsch** *et al.*, 2008). Team self-correction training, or dimensional team training, is a specific type of self-correction that has been found to improve both taskwork and teamwork performance (**Gurtner** *et al.*, 2007).

(3) Knowledge development training is a way to help scientific teams collaborate to solve problems by improving both knowledge building and knowledge sharing. It has been shown that training in knowledge-building leads to improved knowledge transfers, knowledge interoperability, cognitive congruence, and higher overall team performance with a task (**Rentsch** *et al.*, 2010).

(4) Team coordination training is specifically designed to help teams modify their response strategies to changing environmental conditions in a timely manner. This process-oriented training method helps teams deal with variability in coordination demands. Research has shown that teams trained in "disruptions" or "perturbations" are often able to adapt to stressful situations by using effective coordination strategies. As such, they tend to perform better in their collaborations (**Gorman** *et al.*, 2014).

(5) Team building is perhaps one of the most appropriate training methods for cross-disciplinary teams to improve attitudes. It focuses on improving behaviors and relationships within teams (**Payne**, 2001).

In addition to team training, the knowledge, skills, and attitudes associated with team science can also be enhanced through undergraduate and graduate education. Examples include attending courses, seminars, and workshops taught by interdisciplinary faculty; being mentored by faculty from multiple disciplines; working with others who are interdisciplinary trainees; and joining an institutional environment that supports interdisciplinary research.

4.4.7. Measurement and evaluation of team science

The brown cluster in Figure 4 comprises keywords like evaluation, publication, assessment, research productivity, collective intelligence, innovation, bibliometrics, and citations. The focus of these keywords is, therefore, on the measurement and evaluation of team science.

Increased funding of team science has raised questions within the scientific community about the effectiveness of team approaches relative to more traditional, solo science. This makes it necessary to evaluate whether team science programs have indeed played a significant role in advancing science (**Croyle**, 2012; **Klein**, 2008). The evaluation of team science aims to identify, measure, and understand the processes and outcomes of team collaborations (**Mâsse** *et al.*, 2008), which is the primary way to measure team effectiveness and assess the importance of various factors to team collaboration. Through such evaluations, the potential mediators and moderators of successful team science outcomes can be understood, and lessons can be learned about the investment direction and management tactics that should be implemented for subsequent team science programs.

Evaluating collaborative outcomes is the most common evaluation dimension in team science. Assessors have tended to rely on publication data as metrics of collaborative outcomes. Generally, bibliometric methods are used to evaluate the quantity and quality of the outcomes (**Hall** *et al.*, 2018). In addition, bibliometrics can also be combined with other research methods, such as altmetrics, questionnaires, interviews, and social network analysis, to explore the processes of team science and their relationships to research outcomes. The collaborative outcomes that are generally evaluated include publications, citations, applications, social benefits, innovations, etc. Typically, there is also a focus on exploring which team composition maximizes these measures (**Liu** *et al.*, 2020), as shown in Table 5. However, evaluation processes often need to be conducted in conjunction with the developmental stages of team science programs. For example, it would make sense to evaluate the indicators of collaboration readiness in a near-term assessment, the indicators of translation and innovation in a mid-term assessment, and indicators like societal impact in a long-term assessment (**Hall**; **Feng** *et al.*, 2008).

> Researchers who collaborate across disciplines may face challenges in understanding and integrating perspectives from different disciplines, so creating more team communication platforms and training opportunities are needed

Table 5. The evaluation dimensions of collaborative outcomes

Collaborative outcomes	Description
Publications	Which team composition leads to more publications?
Citations	Which team composition leads to more citations?
Applications	Which team composition leads to more patents?
Quality	Which team composition leads to higher-quality research?
Social benefit	Which team composition leads to higher social benefit?
Innovations	Which team composition leads to the most innovative or disruptive science?

In addition to evaluating these outcomes of team science, the collaborative process itself also needs to be measured, as it is this process that governs the functioning and development of the team. The collaborative process specifically includes how team members interact, communicate, and collaborate with each other. In the process of scientific collaboration, the ability of a team to perform a wide variety of tasks is called collective intelligence, which directly relates to team performance (**Woolley** *et al.*, 2015).

Some studies have found that a team's capacity for collective intelligence is strongly correlated with the average social perceptiveness of team members (i.e., the degree to which each individual collaborates with others) but only moderately correlated to the average or maximum intelligence of the team members (**Woolley** *et al.*, 2010). It has also been suggested that the two factors that influence a team's collective intelligence are team composition (e.g., age, gender, diversity, and skill of members) and team interaction (e.g., structure, processes, and norms) (**Woolley** *et al.*, 2015). In addition, research on team performance has found that team performance and creativity are more related to the social processes of team interaction than individual personality traits (**Cross**; **Love**, 2017). Further, research on team creativity and innovation has found that the three key predictors of team success are team membership, engagement rules, and interaction patterns (**Cross**; **Love**, 2017). Therefore, the collaborative process is an important factor influencing the team's success.

Unlike measuring collaborative outcomes, analyzing collaborative processes generally requires using qualitative methods such as questionnaires and interviews. When measuring the effectiveness of team interactions or exploring the impact of certain factors on team processes, researchers generally take the form of scales to conduct research. For example, F. Martín-Alcázar designed a scale for measuring the social capital of research teams in terms of relational, cognitive, and structural dimensions (**Martín-Alcázar** *et al.*, 2019). It is worth noting that many factors can affect the antecedents, processes, and outcomes of team collaboration and should be considered when evaluating team science.

5. Conclusion and discussion

A dramatic increase in the scale and complexity of science and technology, increasing specialization, and a transition from individual innovation to collaborative discovery have characterized the past century. This shift has been driven by high expectations for "team science", which holds that researchers working in teams will achieve breakthroughs otherwise difficult to attain through individual or simply additive efforts. In this work, we have provided a comprehensive overview of the science of team science (SciTS) by combining a systematic literature review with bibliometric methods. Starting from the related concepts and connotations of the team and team science, we have outlined the important events in the emergence and development of SciTS, discussed its foundational theories, and summarized the characteristics of the literature and its seven main streams of research, which are: the definition and theory of SciTS, team composition and collaboration patterns, team formation and team functioning, the physical environment and culture of teams, institutions and organizations for teams, training and education, and the measurement and evaluation of team science.

Our work reveals that the field of SciTS is growing and evolving, with an increasing number of relevant academic papers, books, tools, and academic conferences. The field is also receiving more and more attention and support from some well-known institutions, such as *NIH*, *Elsevier*, the *U.S. Army Research Office*, and others. However, as an emerging field, SciTS's development inevitably faces challenges and achieves breakthroughs that require urgent attention and study by relevant researchers. We have assembled a list of suggestions that we feel, based on our review, are key to further advancing the field.

1) Focus on theories, methods, and tools for interdisciplinary collaboration, and build mature theoretical and methodological systems describing SciTS. Currently, the SciTS field has not yet established a fully mature theoretical and methodological system and a more mature and recognized disciplinary paradigm. For example, definitions of core terminology and typologies of practice and theory related to SciTS too often remain impressionistic or narrow; methodological approaches are limited; and gaps remain in the translation of theory into team science practice (**Falk-Krzesinski** *et al.*, 2011). Therefore, a mature SciTS theoretical and methodological system is urgently needed.

> SciTS focuses on improving the overall team efficiency and to some extent may overlook the growth of the individual scientist

These systems need to relate to the foundation and future development of SciTS. Considering that SciTS is closely related to scientometrics and the interdisciplinary sciences, it is necessary to integrate theories, methods, tools, and research findings within these two disciplines in the future and combine them with specific research settings to build a theoretical and methodological system of SciTS in which theory and practice are mutually reinforcing.

> The SciTS field has not yet established a fully mature theoretical and methodological system and a more mature and recognized disciplinary paradigm, which require urgent attention and study by relevant scholars

2) Inspire scholars from more countries to participate in SciTS to build a multicultural and multi-stakeholder subject area. The field of SciTS has been developing for nearly two decades since its emergence. For a long time, Western countries have played an important role in the organization and participation of the *International Science of Team Science Conference*. We counted the countries to which the corresponding authors belonged and found that the leading countries of SciTS articles involved only 34 countries. The United States is overwhelmingly dominant in SciTS, while most countries, especially African countries, are rarely engaged in this field. Given that contemporary team science is dominated by the United States, this may raise a risk that large team science organizations or programs will likewise be dominated by people from those countries. Instead, people from other countries may inadvertently crowd out organizations or programs, leading to science that focuses unduly on the preoccupations of a small subset of humanity (**Medin** *et al.*, 2017). Moreover, there may be a "preference" in the funding of projects, thereby increasing the risk of scientific conservatism. To mitigate the risk mentioned above, we call for researchers from more countries to participate in SciTS to bolster underrepresented groups in team science.

3) Investments in team science initiatives need to be strategic, with the flexibility to adjust funding amounts based on evaluation results. Although team science initiatives can help facilitate the solution of complex problems, there are still some skeptical voices. Some scholars argue that team science initiatives consume a great deal of money, human labor, and material resources (**Morgan** *et al.*, 2003), while the value-added contributions to scholarship, training, and public health may not be evident for several decades (**Marks**, 2006; **Weissmann**, 2005). This is because team science initiatives and large-scale collaborative teams often require a good deal of preparation work to get everything organized and functioning well (**Brazil**, 2021). In addition, organizing researchers into collaborative centers or large-scale teams does not necessarily lead to more effective work than working independently or as collaborators in small-scale teams (**Marks**, 2006; **Weissmann**, 2005). Indeed, some research questions may be more appropriately addressed using interdisciplinary approaches, while others can be accomplished more efficiently by smaller-scale, unidisciplinary projects (**Stokols**; **Hall** *et al.*, 2008). Therefore, investments in team science initiatives need to be strategic and should be reserved for those research topics that are best suited to and would benefit most from interdisciplinary collaborative approaches. Public institutions and private foundations must be able to choose to increase, suspend, or terminate their investment efforts in team science initiatives based on evaluation results.

4) Improve talent evaluation and team evaluation mechanisms to mitigate any inequalities that may arise or be exacerbated. When forming interdisciplinary teams to address big societal problems, researchers who are invited to join the teams may benefit more in terms of visibility, received citations, work experience, and networking opportunities than those who are not invited. This may lead to increased inequality among researchers and, on a higher level, among universities (**Liu** *et al.*, 2020). In addition, large-scale team science initiatives or programs are generally dependent on investments by public institutions and private foundations. Hence, teams without investments but with new ideas may be at a natural disadvantage compared to those that are funded. Therefore, it is necessary to improve talent evaluation and team evaluation mechanisms, innovate evaluation methods and evaluation indicators, and increase the scrutiny of program selection and investment, thus helping to alleviate any inequalities that may arise or be exacerbated.

5) Focus on personal growth in teams and customize personalized growth plans. Personal growth in teams has been somewhat neglected. SciTS focuses on understanding and enhancing the conditions, processes, and outcomes of team science, with the goal of improving the overall team effectiveness. Yet, in this endeavor, the growth of the individual scientist often gets overlooked, which is likely to constrain creative thinking, curtail due credit, and undermine career progression. Therefore, understanding how individual scientists learn, progress, and innovate in teams is also urgently needed. One such strategy for cultivating personal growth within a team may be to first make a personal development plan by combining the team's development goals and the individuals' growing needs. Second, train individuals on their professional theoretical knowledge and work skills. Finally, conduct a comprehensive assessment of personal growth and any improvements in ability on a regular basis.

6) Develop more team communication platforms to reduce any bias in understanding caused by interdisciplinary collaboration. Integrating different perspectives within an interdisciplinary team can often be difficult, but members are likely to benefit from a broader range of perspectives, experiences, and expertise. However, researchers in these situations may have problems with language barriers and communication, find it difficult to navigate the different structures or procedures of different institutions and disciplines or find it confronting to understand and integrate different views across

disciplines (Yu *et al.*, 2019). Therefore, a big issue is dealing with the different perspectives of researchers from varied disciplines and ensuring they communicate effectively with each other. When divergent views exist, they may also be accompanied by issues such as team conflict, psychological safety, and role ambiguity. Therefore, more communication platforms need to be developed to facilitate communication and understanding in interdisciplinary collaboration and to accelerate the achievement of team goals.

Limitations

There are several limitations to our work that need to be further considered.

First, the retrieval terms we used to assemble our samples were not comprehensive. In a broad sense, studies related to "team" and "collaboration" can be considered team science research, but such a broad scope makes it more difficult to retrieve and analyze the content. Therefore, we used "team science" as retrieval terms, which are more precise but may mean some relevant works of literature were overlooked. In future studies, we will balance precision with comprehensiveness and prepare a more sophisticated search strategy.

Second, SciTS is an emerging interdisciplinary field in its early stages of development. Its future development directions and research focus are yet to be thoroughly studied. Our suggestions for future areas of research are just that –suggestions. These ideas need to be combined with in-depth discussions with experts across multiple fields to map out a solid future agenda for the field.

In conclusion, we hope that more outstanding scholars can be attracted to join the research in this field. We also hope that research management organizations will pay more attention to the important values and significance behind team science to help jointly promote the orderly development of SciTS.

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