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Science facilitation: navigating the intersection of intellectual and interpersonal expertise in scientific collaboration

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Today's societal challenges, such as climate change and global pandemics, are increasingly complex and require collaboration across scientific disciplines to address. Scientific teams bring together individuals of varying backgrounds and expertise to work collaboratively on creating new knowledge to address these challenges. Within a scientific team, there is inherent diversity in disciplinary cultures and preferences for interpersonal collaboration. Such diversity contributes to the potential strength of the created knowledge but can also impede progress when teams struggle to collaborate productively. Facilitation is a professional practice-based form of interpersonal expertise that supports group members to do their best thinking. Although facilitation has been demonstrated to support group functioning in a wide range of contexts, its role in supporting scientific teams has been largely overlooked. This essay defines scientific facilitation as a form of interactional expertise and explains how facilitating scientific teams requires skills in managing interpersonal interactions as well as understanding how different types of disciplinary knowledge integrate in the creation of new knowledge. Next, it explains how this science facilitation expertise may be developed through metacognition. Finally, it provides examples of how scientific facilitation could be more widely incorporated into research by describing three pathways to expand the use of facilitation theory and techniques in collaborative scientific research: developing facilitation skills among scientists leading teams, using broadly trained facilitators, and using specialised science facilitators. The strengths and risks of each path are discussed, and criteria are suggested for selecting the right approach for a given team science project.

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Introduction: The complexity of team science

The complexity of today's most urgent societal challenges is transforming how scientists do their work. Projects and papers involve increasing numbers of authors and institutions (Jones et al., 2008), reflecting the transition from individual projects towards a new normal involving groups of scientists working together. Succeeding in such collaborative science settings creates a need for scientists to manage interpersonal, intellectual, and project management aspects of teamwork (Boix Mansilla et al., 2016; Love et al., 2021; Ulibarri et al., 2019; Zhang et al., 2020). This imperative has been widely recognised in discussions of "team science" (Fiore, 2008; Read et al., 2016; Stokols et al., 2008), which was defined by the National Research Council (National Research Council NRC (2015), p. 22) as "research conducted by more than one individual in an interdependent fashion, including research conducted by small teams and larger groups."

A key premise of team science is that the team forms an interdependent unit, whose collective intellectual productivity is presumed to be greater than the sum of its constituent individuals (Barge and Shockley-Zalabak, 2008; De Montjoye et al., 2014; Fiore, 2008). A team science process rests on a foundation formed from interactions between group members as they together define a problem and make a research plan to address it. In this sense, collaborative knowledge creation is a social process. Historically, knowledge creation has been framed in terms of individual creativity, but recent studies have emphasised the social processes behind creativity and the contribution of interpersonal relationships (Boix Mansilla et al., 2016; Csikszentmihalyi, 1998; Love et al., 2021; Phelps et al., 2012; Sawyer, 2003; Ulibarri et al., 2019; Zhang et al., 2009). These and other scholars increasingly recognise the important role that group dynamics play in the scientific process. This is where facilitation—and we argue, specifically science facilitation—comes in.

Facilitation is a professional practice-based form of expertise that supports members of teams to do their best thinking (Kaner, 2014). Facilitation can help create group processes that are equitable and inclusive, that engage the wisdom and creativity of every group member, and that allow everyone involved to actively participate and listen to all voices (Bens, 2017; Bunker and Alban, 2012; Hogan, 2005; Hunter, 2009; Schuman, 2005). Intentional facilitation helps participants develop engagement and their sense of ownership over group outcomes (Parker, 2020). Facilitation is widely used, including in public policy, corporate governance, industrial project management, and non-profit contexts (Carcasson and Sprain, 2016; Chrislip and Larson, 1994; Means and Adams, 2005; Tabaka, 2006). Facilitation has previously been suggested to improve the effectiveness of scientific teams. Yet what past examinations of facilitation in scientific settings have overlooked is how the nature of scientific teamwork necessitates a distinct approach to facilitating team science. The heart of facilitation expertise in non-science settings tends to focus on supporting groups to make decisions about actions they will take (Kaner, 2014) or resolve conflicts (Carcasson and Sprain, 2016; Carpenter and Kennedy, 2001). In contrast, science teams' main objective is to generate new knowledge (Salazar et al., 2012); this objective influences how team processes unfold and thus determines the kinds of support a facilitator needs to provide.

Although it is certainly possible for scientific teams to work together without the knowledge offered by facilitation practice, we argue that facilitation expertise elevates and accelerates the work of team science. Our purpose in this essay is therefore to articulate the value and practice of science facilitation. We define *science facilitation* as comprising three things: (1) a *role* within a scientific team that is best filled by someone who uses a distinct form of (2) *practice-based expertise* to guide teams in (3) the *process* of scientific collaboration. Throughout this paper we will refer to all three parts of this system, but we will focus primarily on the concept of science facilitation expertise, which we understand as existing at the intersection of scientific collaboration expertise and interpersonal expertise. We thus conceive of scientific facilitation as a distinct form of interactional expertise (Bammer et al., 2020). Interactional forms of expertise are usually tacit, codified by "learning-by-doing," and augmented from project to project; therefore, they can be difficult to measure and may be rarely documented in literature (Bammer et al., 2020).

In the remainder of this essay, we describe in detail science facilitation expertise (section "Science facilitation: the intersection of collaborative science expertise and interpersonal expertise") and explain how it can be developed through reflection (in-action and on-action; Schön, 1983, 1987) and metacognitive practices (section "Developing and applying science facilitation expertise through reflective practice and metacognition"). We then discuss three distinct pathways for how science facilitation expertise might be more widely incorporated into research practice: developing facilitation skills among scientists leading teams, using broadly trained facilitators in scientific collaboration settings, and using specialised science facilitators. We discuss the pros and cons of each pathway and suggest criteria for selecting the right approach for a given project. In making this argument, we seek to help make science facilitation expertise more visible to support scientific teams to be better able to solve complex and urgent problems.

Science facilitation: the intersection of collaborative science expertise and interpersonal expertise

One of the key insights of the recent, rich body of work on the science of team science (SciTs) is that effective collaborative knowledge generation requires a combination of collaborative science experience *and* facility with the interpersonal team dynamics that contribute to effective collaboration (Hall et al., 2018).

Scientific collaboration expertise. The ultimate goal of scientific collaboration is to produce new knowledge. Like any scientific process, this requires defining a research question, defining methods to answer it, identifying or collecting data, analysing data, producing scholarly products, and translating results to people who can use them. In team science settings, this process of creating and sharing new knowledge is the collective responsibility of an interdependent team of scientists (National Research Council NRC (2015); Table 1). As a result, the process of developing, refining, and implementing group ideas can be complex and challenging. Early in a project, scientific teams need to develop a shared vision of their research scope, brainstorm research questions, and agree on methodologies to approach a challenge (Hall et al., 2012). Later in a project, teams must decide how to jointly collect data, address data sharing, assess evidence and reconcile different interpretations into a manuscript (Hall et al., 2012). The interdependent nature of team science means that teams must find ways to ensure that all team members are progressing through the stages of scientific problem solving at the same rate and pace, for example by encouraging a period of divergent, creative thinking and then making sure that everyone is ready to switch to evaluating the ideas generated and converging on an agreed path forward (Ulibarri et al., 2019). To do this, teams need psychological safety (Edmondson, 1999) so individual members feel comfortable sharing bold ideas, honestly evaluating those of their teammates, and ultimately integrating the best ideas to move the team forward.

Table 1 Key terms related to interdisciplinary, applied, and collaborative science approaches.

Term	Definition and source	Includes bridging across disciplines	Includes solving real-world problems	Includes interdependent team doing science
Actionable science	"Societally engaged sustainability research that improves use in decision-making" (Arnott et al., 2020, p. A1).		X	
Breakthrough science	Science whose ultimate goal is to integrate different types of knowledge to solve real-world challenges (current article, following Read et al., 2016, p. 7: "To make scientific breakthroughs with complex, large-scale problems, society depends on collaborative teams of scientists to effectively exchange information across disciplinary boundaries")	X	X	
Convergence research	National Science Foundation (NSF) identifies Convergence Research as having two primary characteristics: "(1) Research driven by a specific and compelling problem. Convergence Research is generally inspired by the need to address a specific challenge or opportunity, whether it arises from deep scientific questions or pressing societal needs and (2) Deep integration across disciplines. As experts from different disciplines pursue common research challenges, their knowledge, theories, methods, data, research communities and languages become increasingly intermingled or integrated. New frameworks, paradigms or even disciplines can form sustained interactions across multiple communities" (National Science Foundation (NSF), 2022)	X	X*	
Integration	High end of "level of interaction and integration spectrum". In an integrated research team: "(1) Each team member brings specific expertise to address the research problem; (2) Teams meet regularly to discuss team goals, individuals' objectives, and next steps; and (3) Team shares leadership responsibilities, decision-making authority, data, and credit" (Bennett et al., 2010, p. 9)			X
Integrative applied research	"Integrative applied research is a research style that deals with complex real-world problems by bringing together disciplinary and stakeholder knowledge and explicitly dealing with remaining unknowns, in order to use that integrated research to support policy and practice change. An integrative applied research team is composed of investigators from a range of disciplines...Many, but not necessarily all, team members also have expertise in the complex real-world problem under consideration. The team	X	X	X

Table 1 (continued)

Term	Definition and source	Includes bridging across disciplines	Includes solving real-world problems	Includes interdependent team doing science
	explicitly interacts with stakeholders, policy makers and practitioners" (Bammer, 2013, p. 18).			
Interdisciplinary research	"[A]n interactive process in which researchers work jointly, each drawing from his or her own discipline-specific perspective, to address a common research problem" (Stokols et al., 2008, p. S79).	X		X
Multidisciplinary research	"[A] sequential process whereby researchers in different disciplines work independently, each from his or her own discipline-specific perspective, with a goal of eventually combining efforts to address a common research problem" (Stokols et al., 2008, p. S79).	X		
Team science	"Scientific collaboration, i.e., research conducted by more than one individual in an interdependent fashion, including research conducted by small teams and larger groups… Most team science is conducted by 2–10 individuals, and we refer to entities of this size as science teams" (National Research Council NRC (2015), p. 22).			X
Transdisciplinary research	"[A]n integrative process in which researchers work jointly to develop and use a shared conceptual framework that synthesises and extends discipline-specific theories, concepts, methods, or all three to create new models and language to address a common research problem" (Stokols et al., 2008, p. S79).	X		X
Translational research	"Translational research refers to translating research into practice, i.e., ensuring that new treatments and research knowledge actually reach the patients or populations for whom they are intended and are implemented correctly" (Woolf 2008, p. 211)		X	
Usable science	"Usable science is [science] produced to contribute directly to the design of policy or the solution of a problem. This implies a much more specific, time sensitive role for science to be used in supporting decisions as they exist today or in the near future" (Dilling and Lemos, 2011, p. 681).		X	

For each scientific approach, we identified one widely cited definition from the literature (column 2). In reviewing the terms, we identified three key dimensions that differentiate these scientific approaches: bridging between diverse disciplines to create new knowledge, solving real-world problems, and/or interdependent teams collectively producing science. For each scientific approach, we assessed whether the selected definition explicitly mentioned each dimension (columns 3–5). The * on the X for convergence research recognises that National Science Foundation (NSF)'s definition includes "deep scientific questions or pressing societal needs".

Scientific collaboration requires not only intellectual coordination, but also logistical organisation of resources (i.e., money, people's time, scientific equipment, etc.) and management of the group's collective effort to ensure work proceeds. In the early stages of a project, groups must develop systems for working together, including shared document systems, meeting agendas, email lists, and the like. As a project proceeds, a team needs to create work plans, make decisions about assigning responsibility for completing tasks, trade off between competing objectives, troubleshoot logistical challenges, and often overcome resource constraints. Depending on the collaboration and the administrative or institutional support available, the team might also be responsible for tasks like coordinating submission of team grants, planning workshops or events, accounting for shared funds, and so on.

The challenge of collaboration becomes even greater in settings when teams include diverse members from different disciplines or when scientific objectives are focused on solving applied, real-world problems (Matthews et al., 2019; Read et al., 2016). Around the globe, science agencies and funders are increasingly focusing on science that combines disciplines to solve challenging problems, including the U.S. National Science Foundation (NSF, 2017), Horizon Europe (Schiermeier, 2021), and the Australian Council of Learned Academics (ACOLA; de Vos Malan, 2016), among others. These diverse calls for updating how science is practiced share a common recognition that the deep understanding needed to solve thorny societal challenges simply cannot be achieved within an individual discipline or professional field (Lang et al., 2012).

Despite the common recognition of the needs, a wide range of terms are used to describe scientific research approaches that do one or more of the following: (a) bridge across diverse disciplines, (b) address real-world problems, and/or (c) require collaboration among an interdependent team of scientists. We argue that science facilitation is beneficial when any of these conditions are met, and particularly for projects that address two or three of these goals. We have created Table 1 to highlight some of the most commonly used and discussed of these approaches. For each approach, we categorise whether a widely-cited definition in the literature explicitly specifies each of these three dimensions. We note these interconnected scholarly discussions are continually evolving, and these terms may be defined differently by different authors. Recognising that, we nonetheless believe that science facilitation broadly, and this paper specifically, is relevant to anyone whose work incorporates any of the dimensions captured in Table 1.

In this article, inspired by Read et al. (2016; see Table 1), we use the term *breakthrough science* to refer to science whose goal is to integrate different types of knowledge to solve real-world challenges. This definition overlaps with NSF's definition of convergence research (National Science Foundation NSF, 2022), but in our roles as facilitators we have found "convergence" as a description of the overall research effort sometimes confuses teams. As described in more detail in the section "Interpersonal expertise", in the team dynamics and problem-solving literatures that provide part of the foundation for facilitation practice, convergence is the final stage of a group decision making or knowledge creation process. There are numerous steps before convergence which may include: forming, storming and norming (Tuckman, 1965); divergent thinking and the creative disagreement of the "groan zone" (Kaner, 2014), and development, integration, and conceptualisation (Hall et al., 2012).

Multiple scholars have argued that competence in breakthrough science settings constitutes a distinct form of scientific expertise. Bammer (2017, p. 2) argues that

> "Team-based interdisciplinarity addressing complex societal and environmental problems needs specific expertise over and above that contributed by disciplines. This set of knowledge and skills is currently poorly defined and recognised…. Integration and implementation scientists… contribute to teams requiring expertise in exploring a complex problem more comprehensively. They…assist teams in figuring out how best to approach the problem and its interconnections, which disciplines and stakeholders need to be involved, how to bring together the various disciplinary and stakeholder perspectives, how to take into account what is not known about the problem, how to support those charged with acting on the problem, and other related issues."

Similarly, de Vos Malan (2016, p. 1) delineates transdisciplinary research as necessitating four key "specialised skills" that experienced project managers or conveners should possess: "the capacity for rigorous scoping [of real-world problem spaces]; the development of a collaborative culture; familiarity with serious and pervasive ambiguity; and a clear understanding of target audiences." These are just a few examples of how diverse literatures identify the need for scientific collaboration expertise, a key component of science facilitation expertise.

Interpersonal expertise. The interdependent nature of team science means that interactions between group members are intimately related to the scientific success of collaborative projects (Love et al., 2021).

Effective teamwork in any field, including science, requires actively overcoming common team dysfunctions, including absence of trust, fear of conflict, lack of commitment, avoidance of accountability, and inattention to results (Lencioni, 2002). Much of the psychological and organisational behaviour research on teams is focused on best practices for addressing these and other potential barriers to effective teamwork; facilitation is a practice-based field that applies such insights (e.g., Bens, 2017; Hogan, 2005; Schuman, 2005). For instance, in the early stages of a project, scientific teams can benefit from developing team norms and shared expectations for how they will work together (i.e., team values or ground rules (Duhigg, 2016; Hall et al., 2012) or developing collaboration agreements that explicitly address topics such as institutional arrangements, data sharing, team member time commitments, authorship, and how the team will access funding or other necessary resources for its work (Gadlin & Jessar, 2002; Penn State Clinical and Translational Science Institute, 2021). Common models of team development describe a cyclical process of team dynamics with periods of uncertainty, conflict, or chaos that teams pass through before achieving their final goals (Hall et al., 2012; Kaner, 2014; Tuckman, 1965). In such periods of uncertainty or conflict, someone serving in a facilitator role can assist a team to listen productively to one another, recall team agreements, and serve as a mirror or "outsider lens" to help the team see its behaviour or work more objectively (Kaner, 2014).

The importance of interpersonal expertise in collaboration has also received attention from scholars of team science. Developing ideas with other scientists or practitioners, especially those with different academic or professional backgrounds, requires that team members experience a level of psychological safety (Duhigg, 2016; Edmondson, 1999) that allows them to ask questions, submit unproven theories to scrutiny, and risk sharing half-baked or undeveloped ideas (Clark, 2020; Morisette et al., 2017). Bozeman et al. (2013) argue that the membership of a team is less important to determining the success of a scientific collaboration than the nature of the interactions between the people in the room. Boix Mansilla et al (2016) highlight the importance of emotional interactions between team members, suggesting that

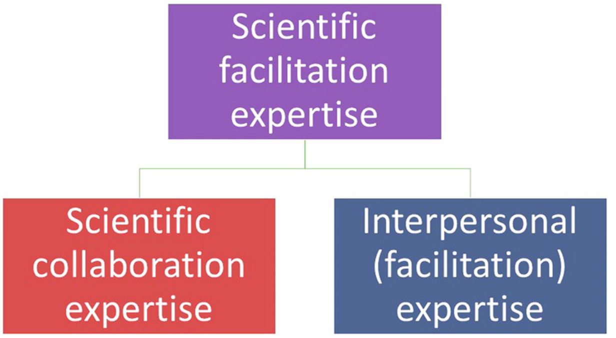

Fig. 1 The composition of science facilitation expertise. Science facilitation expertise is a combination of expertise in scientific collaboration and interpersonal expertise as applied to facilitation practice.

successfully framing a scientific problem requires quality emotional engagement. Using social network analysis, Zhang et al. (2020) identify a link between team outcomes and team members' average emotional intelligence. Similarly, Ulibarri et al. (2019) argue that empathy and self-awareness (both aspects of emotional intelligence) can be used proactively to aid collaborative research and Love et al. (2021) describe how interpersonal relationships drive successful team science.

Science facilitation. We conceive of scientific facilitation as a distinct form of professional expertise that exists at the intersection of scientific collaboration expertise and interpersonal expertise (Fig. 1). Scientific facilitation represents the application of interpersonal skills and facilitation practices to the distinct challenge of collaboratively solving scientific problems. In other words, one must know when and how to intentionally take action to move teams through their scientific work (Graef et al., 2021). Such movement happens on multiple timescales: moment-to-moment within a meeting, day-to-day over the course of a multi-day workshop, and week-to-week or month-to-month as a project unfolds. Two characteristics define the unique nature of scientific facilitation: its goal of knowledge creation (as opposed to decision-making or conflict resolution) and the central importance of bridging between diverse scientific cultures (Strober, 2010).

Scientific teams are focused on knowledge creation rather than decision-making. Most of the literature on facilitation to date has focused on supporting groups to make decisions about actions they will take (Kaner, 2014) or resolve (sometimes deep-seated) conflicts (Carcasson and Sprain, 2016; Carpenter and Kennedy, 2001). In contrast, science teams' primary objective is to generate new knowledge (Salazar et al., 2012). Knowledge creation involves working at the fringes of what is currently known, which shapes the nature of agreement and disagreement within the team as it collectively moves toward its vision of scientific "truth". This can mean that teams often must begin by explicitly defining core assumptions about a problem or its causes; these core assumptions may or may not be shared among team members. Indeed, one of the defining characteristics of the "wicked" problems that are the focus of so many team science efforts is that the way the problem is described influences one's understanding of the problem and the set of possible solution spaces (Rittel and Webber, 1973). The knowledge creation objective also means that teams need to reach a high level of agreement about their conclusions and final products because scientific traditions of authorship place high burdens of responsibility on each member of a shared author team (International Committee of Medical Journal Editors (ICMJE), 2021)).

The distinction between facilitation for decision making and knowledge creation is subtle (and may blur in some settings where the goal of the science is to influence policy decisions or similarly aid stakeholders), but still real and important in practice. One key distinction is the way a team moves through the phases of divergent thinking and the creative disagreement that Kaner (2014) terms the "groan zone." This is when a team uncovers differing assumptions and eventually reconciles them to create a convergent, shared team vision. In a decision-making process, the heart of disagreement is generally about what action a team will take; the facilitator's role is to help the team understand the interests and preferences of team members and negotiate agreements about moving forward (Kaner, 2014). While different views about what to do may be shaped by underlying values and even identities, principles of interest-based negotiation (Fisher et al, 2011) can often help a team find mutually agreeable solutions without needing to resolve underlying conflicts over values.

In knowledge creation processes, in contrast, the core disagreements in the "groan zone" are often about what quality or rigorous research looks like and how the interdependent team should proceed to produce work on which each individual is comfortable staking their personal scientific reputation. This changes the facilitator's role from helping a team agree on actions it will take to helping the team understand the extent to which underlying core assumptions are shared or not shared between team members. Particularly in breakthrough science settings, where groups are deliberately trying to integrate multiple disciplines and/or span research-practice boundaries, one of the key challenges of collaboration is bridging between diverse scientific cultures, including integrating members' mental models while making explicit concepts and assumptions held by group members that might otherwise be implicit or tacit (Hubbs et al., 2020). Hall et al. (2012) describe the development stage where teams develop a shared language so they can eventually progress to more advanced stages: conceptualisation, implementation, and translation.

Enhancing cross-disciplinary communication and developing shared understanding within the team thus becomes an essential milestone for breakthrough science teams (Hubbs et al., 2020; O'Rourke and Crowley, 2013). One person's common terminology is another person's jargon, and conflicts over terms can be a common source of conflict. Such conflicts often reveal differences in underlying assumptions about how rigorous research is conducted which are deeply embedded, sometimes unconsciously, in scientists' epistemologies, ontologies and methodologies (Khagram et al., 2010; Moon et al., 2019). For example, some (often natural science) disciplines insist that all research is driven by hypothesis testing while other (often social science or humanities) disciplines regularly begin projects with exploratory statements and rarely use hypotheses. Questions to explore these sorts of differing starting assumptions are the focus of the ToolBox Dialogue project (Hubbs et al., 2020). Resolving such foundational conflicts and coming to mutually agreed upon definitions of terms is critical for scientific teams to achieve their research goals (Hall et al., 2012). Science facilitators can provide structured activities that help teams make progress to address these types of challenges while helping create an atmosphere that promotes psychological safety (Duhigg, 2016).

Science facilitators use scientific collaboration expertise and interpersonal expertise simultaneously and interdependently to guide a team as it moves through the complex process of collaborative scientific work. All professional skill sets are built on a foundation of experience and knowledge; humans often learn by connecting new information to what is already known (Grippin and Peters, 1984). For example, an individual learns to cook from family, personal experience, recipes, books, and numerous other life experiences. These experiences build, iterate, and ultimately contribute to a person's culinary outputs at any given meal. Similarly, the types of training and professional activities a facilitator has experienced comprise the contents of a metaphorical "recipe box," a mental repository of facts, processes, situations, and lessons learned. One key difference among facilitators is the contents of their recipe box. For each person, the information in the recipe box will be unique. The next section describes how a facilitator might develop their own unique recipe box through reflection-in-action, reflection-on-action, and metacognition.

Developing and applying science facilitation expertise through reflective practice and metacognition

Here we draw on theory from the learning sciences to explore what constitutes professional expertise and how someone develops it in a field like science facilitation. Specifically, we use Schön's (1983, 1987) description of professionals as "reflective practitioners" who progressively develop more effective abilities to react to situations they encounter in real-world practice. Schön's work and related work on reflective practice (e.g., Harvey et al., 2016; Johns, 2017) emphasises that the development of expertise is grounded in a combined awareness and analysis of oneself as a learner and the accumulation of relevant professional experiences (i.e., one's ever-growing recipe box), from which one draws lessons that contribute to the development of specialised professional intuition. Deep expertise in a practice-based field like science facilitation develops from experience grounded in reflection-on-action and reflection-in-action (Fig. 2).

Reflection-on-action is a common component of experiential learning in which a person has an experience and reflects on it later to identify important lessons or qualities. In the recipe box, this process may be thought of as sorting and indexing the situations that give one insight into a professional field. For facilitators, reflection-on-action consists of consciously reflecting on group processes in which one served as a group member or facilitator to understand how the facilitator's actions influenced outcomes for the group. Reflection-on-action can guide follow-up activity and planning for subsequent meetings, as part of responding to critical incidents from prior meetings and planning next steps. As a person participates in and reflects on more and more group processes, they develop a richer body of practice-based knowledge about what does or does not work in particular situations. In other words, they grow from having the recipe box of a beginner to that of a skilled, intuitive chef.

In contrast, reflection-in-action "reshapes what we're doing while we're doing it" (Schön, 1987, p. 26). It is a dynamic process that occurs simultaneously with practice and is often equated with thinking on one's feet, key for responding in real time during a facilitation. Schön highlights that when experienced practitioners are observing a situation, they are implicitly comparing it to past situations they have previously encountered. This can be thought of as scanning through one's recipe box to find the past situation(s) that best match what is currently being encountered. Greater numbers of cases in one's recipe box provide greater numbers of cases to draw on in this process, which Schön termed "thinking with exemplars." Reflection-in-action is thus analogous to the cook who realises a key ingredient is missing midway through the preparation of a soup but is instantly able to pull the recipe for a different soup out of their recipe box. In facilitating, skills such as reading a room of participants and adapting activities to suit, or reacting to unforeseen occurrences, such as uncovering a disruptive piece of information, are examples of reflection-in-action happening in practice.

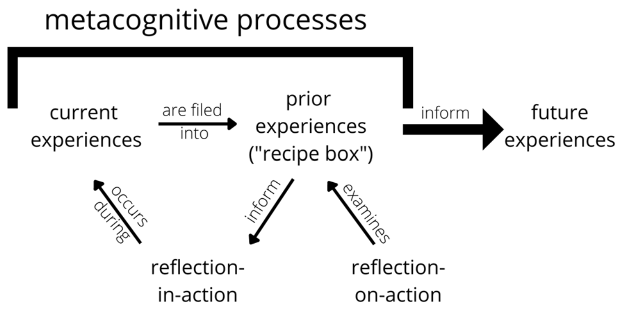

Fig. 2 Metacognitive processes that support learning from experience to inform future experiences. Reflection-on-action is experiential learning based on past experiences. Reflection-in-action is real-time reflection to link current experiences with relevant past experiences.

Taken as a whole, reflective practice enables facilitation professionals to develop their skillset based on a thoughtful grounding in the experiences of real-world practice. One's collection of instances of in-the-moment reflection increases over time through those experiences. Conscious reflection on those moments builds and deepens one's understanding of how those moments come about, how they can go well or poorly, and how one might choose to handle them in the future.

Both types of reflection contribute to the process of metacognition, defined as "people's awareness and understanding of their own thinking and learning processes, as well as their regulation of those processes to enhance their learning and memory" (Ormrod, 2016, p. 363). For a facilitator, metacognition encompasses all the mental processes that may be engaged when facilitating a group, from facilitation design before even meeting the team, planning the arc of a project's lifespan, and seeking facilitation resources to bolster approaches as the specifics of the project and participants become more apparent. For example, a facilitator relies on their metacognitive skills to evaluate the task at hand, including the available resources for the team, and to determine which strategies are appropriate for helping the team reach its goals. Facilitators learn from their direct experiences (reflection-in-action), later consideration of those experiences (reflection-on-action), and engage in purposeful, directed progress towards learning goals and opportunities for improvement (metacognition). Over time, an increasing number of practice-based experiences and associated reflections develop and combine into greater professional expertise and skill.

The implication of reflective practice is that practice-based expertise develops from a combination of technical knowledge, accumulating real-world experiences, conscious learning from past experiences, and intentional professional growth. Successfully facilitating in scientific settings requires practice-based facilitation knowledge to be tailored and applied to the specific challenges of collaborative or breakthrough scientific research. The ability to tailor and apply facilitation will depend on the contents of the facilitator's recipe box. For example, a person with extensive science team experience but relatively little interpersonal and facilitation experience might be the right match for an established, productive team grappling with a new or difficult technical challenge. Conversely, if a team has complicated interpersonal dynamics, the facilitator's scientific expertise might matter comparatively less than their facilitation and group processes experience. In essence, the needs of the team need to match with the content of the facilitator's unique repertoire of professional experiences and learning. The next section describes these challenges in greater detail, providing snapshots of the practice-based knowledge required to work effectively in varying scientific settings.

Three pathways: matching science facilitation expertise to a team's needs

Teams who are pursuing collaborative and breakthrough science work across widely varying contexts, including extremes of team size, team funding, and team timelines. Some teams may comprise only a handful of researchers within a single institution working together for a few months to pull together a larger grant proposal. Other teams may span a range of universities, agencies, non-profits, and for-profit companies, and collaborate over years or even decades. Given the importance of science facilitation, how then can team scientists determine what level of expertise they need for a given project?

We propose that there are three pathways scientific teams can follow. For some projects, a team leader or member with deep knowledge of the project or disciplinary field (e.g., principal investigator (PI), co-PI, research administrator or project manager) with some experience or training in facilitation and interpersonal dynamics could play dual roles of facilitator and team member (Path 1), either drawing on skills that already exist in the group or cultivating them. Other projects might need a facilitator external to the group with a much greater degree of interpersonal and facilitation expertise but might not necessarily require someone with deep science collaboration experience (Path 2). The final case is projects that require a person outside the team to serve in the facilitator role and need that person to have specialised expertise in both scientific collaboration and group processes (Path 3). In describing these different paths, we refer to an individual facilitator for simplicity, but co-facilitation or facilitation teams can be critical for supporting bigger scientific teams, scientific teams who are less experienced with facilitation, or for more complicated tasks.

Whether a given team science process falls into Path 1, 2, or 3 will depend on a variety of factors, including: the complexity of the project, the stage of the scientific process, the strength of pre-existing relationships among team members, legacies of prior conflict and the nature of the conflict, the diversity of knowledge systems being brought together within the team, what funding mechanisms provide or demand when it comes to facilitation, the availability of relevant science facilitators, and more (Table 2). Table 2 also includes potential use cases for each path. Teams might also move between paths at different points in a project, as we discuss in Section 5.

Table 2 Key qualities of the three science facilitation pathways.

Facilitator type	Facilitation by scientist within team trained in facilitation (Path 1)	External general facilitators (Path 2)	External science facilitators (Path 3)
Strengths	• Lower cost, assuming facilitator is already a team member	• Professional facilitation expertise	• Combined professional facilitation and scientific expertise
	• Familiar with scientific content and processes	• Presumed neutrality as a project "outsider"	• Presumed neutrality as a project "outsider"
	• Expedited orientation to the team and project	• Can support team members' metacognitive development around team functioning and process	• Can support team members' metacognitive development around team functioning and process
	• Facilitator and team by definition are on same timeline		
Risks	• Likely to have limited facilitation experience compared to professional facilitators	• Potentially higher cost than an internal facilitator	• Potentially higher cost than an internal facilitator
	• May need additional training, requiring time and other resources	• Requires time to orient to the team and project	• Requires time to orient to the team and project
	• May be tension between facilitator role and ability to contribute as scientist	• Limited understanding of scientific or disciplinary processes	• Specialised skill set may be difficult to find or right people may have limited availability
	• Subject to internal power dynamics	• May have less credibility with team members due to lack of understanding of scientific or disciplinary processes	• Unnecessary additional expense for simpler projects
		• Unnecessary additional expense if unable to navigate problems specific to the scientific process	
	No facilitation or suboptimal facilitation could lead to time wasted, a failure to produce necessary knowledge products, loss of trust in facilitation process, or a lack of quality science		
Project characteristics that might be most successful with this approach	• Small teams (<5–10)	• Big teams (>10)	• Big teams (>10)
	• Small budgets	• New teams	• New teams, especially those with diverse scientific composition
	• Internal facilitation expertise already exists in the team	• Occasional important planning meetings or proposal development	• Occasional important planning meetings or proposal development
	• Teams with existing relationships or healthy interpersonal dynamics	• Projects whose complexity comes from interpersonal aspects (e.g., history of conflicts, many institutions, etc.)	• Projects whose complexity comes from knowledge convergence, knowledge integration, or cross-cutting research goals
	• One or more team members are eager to develop facilitation skills	• By default, in situations that are too complex for Path 1 and Path 3 facilitators are not available	

Path 1: Facilitation by someone internal to the team with greater scientific collaboration than interpersonal expertise. For some projects, a project leader or member with some experience or training in facilitation and interpersonal dynamics could play dual roles of team member and group facilitator (Bennett et al., 2010; Eigenbrode et al., 2017). This might include a PI, co-PI, research administrator or project manager, or a graduate student or postdoctoral researcher who is interested in facilitation, but who is involved in the project as a scientist first and a facilitator second. This internal person may have some facilitation experience that predates the project, but they are likely to possess stronger expertise in scientific collaboration than interpersonal and group dynamics The benefits of an internal person filling the science facilitator role is that it may be most affordable (especially if the scientist has previous facilitation training) while also allowing for responsiveness to emergent needs from within the team as the collaboration process progresses. This approach is thus highly flexible, as it does not require finding or hiring an external person to serve in the facilitator role. Another benefit is that it builds capacity within the team and for the individual. For instance, paying for facilitation training for a postdoctoral scientist within a project team and supporting that person to play the facilitator role results in learning for the team over the course of the postdoc's participation and hones a skill the scientist can take with them into future projects.

One of the risks of Path 1 is that basic facilitation training is not the same as experience developed over time through practice and reflection. Like following recipes in a cookbook are only the first step to becoming an intuitive cook, training can start someone along the path of developing expertise, but this option includes the potential for group management mistakes arising from a comparative lack of interpersonal expertise. Other risks include the slowing down of the process as someone finds and attends training, and the difficulty placed on the chosen individual to strike a balance between contributing as a scientist and facilitating the team. It can be exceedingly difficult to both represent one's own research area of interest within the team and simultaneously serve as facilitator, especially if the facilitator role is being filled by someone with less power in the team, such as a more junior scientist, a graduate student, or a member of a marginalised group (e.g., a woman or person of colour in STEM; Carpenter-Song and Whitley, 2013; Gaughan and Bozeman, 2016). Conversely, if the facilitator is someone in an authority role within the project (e.g., programme manager or PI), they may struggle to be seen as neutral by the group or may find it difficult to separate their own vision for the scientific collaboration from their role as the facilitator (Halpern and O'Rourke, 2020; Wróbel et al., 2021). Both of these cases can create tensions for the individual in how they experience their role and can also constrain the contributions that other group members feel comfortable making.

Path 2: An experienced facilitation professional with minimal scientific collaboration experience. A second approach is for the scientific team to hire an external facilitator or facilitation team with general facilitation experience. Such external facilitators will likely bring substantive interpersonal expertise but comparatively less expertise with processes of scientific collaboration. These facilitators have developed their facilitation expertise through reflective practice and metacognition with non-scientific teams working in sectors such as government (including state or federal policy making or local-scale community engagement), non-governmental organisations (NGOs), education, or business.

The strengths of Path 2 arise from the strengths of the field of facilitation itself. An external facilitator brings greater neutrality than a scientist embedded in a team can bring. As a designated person whose job is to pay attention to group dynamics and interpersonal interactions, a facilitator external to the team can stay outside of conflict and approach challenges with fresh eyes. Experienced facilitators bring a wide range of experiences of what has and has not worked in past groups and a multi-faceted toolbox of techniques that can help a group work more effectively together. An experienced facilitator is likely to have established metacognitive practices and can support team members in becoming aware of and developing individual and collective reflective practices around team processes. In addition, facilitators with general experience are likely to be more widely available than specialised science facilitators.

The main risk of Path 2 is that the facilitator's past experiences may or may not be directly applicable to the specific scientific collaboration challenges faced by the team. In essence, they may possess a recipe box for the wrong kind of cuisine. For instance, a facilitator with insufficient experience in scientific collaboration or breakthrough science settings may misunderstand or overlook necessary steps in the collective knowledge creation process, which could undermine the team's ability to produce quality science in a timely way or may pit the team's scientific leadership against the facilitator rather than allowing both to work together to achieve common goals. Facilitators who do not understand the unique epistemological cultures that exist within different scientific disciplines (Strober, 2010) are less likely to choose appropriate structures and processes to effectively leverage the different types of contributory expertise in a group and allow members to engage in productive breakthrough science research (Wardale, 2013). At worst, hiring an external facilitator who is unable to recognise and help the group navigate challenges specific to the scientific process could lead to backlash within the scientific team against the idea of investing in facilitation. Finally, we note that hiring external facilitators generally costs more than having someone within the team attend training and play this role.

Path 3: A science facilitator brings a blend of scientific collaboration and interpersonal expertise. The third path is to hire someone external to the team to serve in the facilitation role who brings a combination of interpersonal expertise in managing groups with intellectual and process expertise in collaborative team science. We term this specialised combination science facilitation expertise.

Science facilitators differ from general facilitators (Path 2) in their repertoire of reflective practice and metacognition from working with scientific teams in the past and they bring a greater depth of interpersonal expertise than would be available if a team member served in the facilitator role (Path 1). As in Path 2, science facilitators can support team members in increasing their metacognition through reflective practices. Thus Path 3 offers the benefits of a higher degree of neutrality and the application of more specialised knowledge and techniques shaped by past work in similar contexts.

In many ways, then, Path 3 offers the best of both worlds. However, we caution that this level of specialised experience will not be necessary for many projects. In addition, finding and paying for such specialisation may be challenging. The number of individuals with the depth of expertise in both facilitation practice and science collaboration to meet our definition of Path 3 science facilitators is still relatively small, though growing fast. As a result, these individuals may be hard to identify, may have limited availability if they can be found, and may not have other desired characteristics (e.g., ability to travel). Like Path 2 facilitators, hiring someone external to the team to guide a group's process carries increased costs and may require additional time to identify and hire the right facilitator. This may be even more of a challenge with Path 3, as the number of job titles and institutional arrangements under which these individuals work is in our experience greater than Path 2 facilitators, who tend to simply be called "facilitators."

Discussion

Bammer et al. (2020) identified and defined two categories of expertise: (1) contributory expertise, expertise required to make a contribution to a field or discipline (Collins and Evans, 2007); and (2) interactional expertise, socialised knowledge that includes socialisation into the practices of an expert group (Bammer et al., 2020). We argue that effectively guiding collaborative science groups—and in particular, those addressing the most pressing global problems that require breakthrough science—requires two intersecting types of interactional expertise: facility with collaborative science and the ability to apply principles of interpersonal dynamics to group facilitation. Collaborative science expertise includes the skills that Bammer (2017) defined as the core competencies of implementation and integration specialists. The broader professional field of facilitation (e.g., Bens, 2017; Hogan, 2005; Kaner, 2014; Schuman, 2005) represents a second form of interactional expertise, a well-developed body of interpersonal theory and practical knowledge for managing complex group processes and helping teams work well together.

One of our goals in advancing a formal definition of science facilitation is to make explicit the tacit interactional contributions and skills that the people doing this work possess. We also argued there are at least three options for how and by whom the scientific facilitation role within a team can be filled. Identifying the most appropriate option requires matching the needs of a given project with the expertise of the person who will fill the role. We presented three paths that capture the major variations we believe are possible (though hybrids might exist) and described pros and cons of each path (Table 2).

For projects that are expected to have minimal conflict or where teams have existing relationships, Path 1—a scientific team member acting simultaneously as facilitator—can be a pragmatic and low-cost arrangement that over time builds science facilitation capacity within the team. Conversely, Path 2 involves a broadly trained facilitator or facilitator team who brings a great deal of facilitation and interpersonal experience, but who is new to applying that expertise in the science facilitation context. For this reason, we argued that Path 3, having someone with balanced expertise in both interpersonal dynamics and science collaboration serve in the facilitator role, is likely the most efficient solution in highly complex breakthrough science settings. However, we recognise that identifying, funding, and hiring Path 3 facilitators can be challenging.

Each of these paths offers value for certain scientific teams, but none of them provides one single model that will work for every situation. For instance, a scientific team might decide to follow different paths at different stages of a scientific collaboration, such as bringing in external science facilitators early on to establish an overarching vision for a project but then relying on internal facilitation for smaller, less consequential meetings. An existing scientific team might also use this rubric to assess their own effectiveness and identify whether they have a path-project mismatch, in which case they might try an alternative path. Finally, we note that all three paths are relatively agnostic as to the institutional home of the facilitator. In particular, a Path 2 or Path 3 facilitator might be employed by a professional facilitation firm, a university, or a funding agency. Nothing in our personal experience nor, to our knowledge, in the published literature suggests that institutional home makes a significant difference to the expertise the individual facilitator brings to their role, though it might be that certain combinations of paths and institutional models offer certain benefits.

Conclusion: recommendations for building capacity for scientific facilitation

Science facilitation is a core function that must be provided for within any well-functioning team science effort. Here we build upon and expand the argument made by Graef et al. (2021, p. 110), who argued that facilitation can serve as a "method to create the conditions for innovative and collaborative forms of [scientific] synthesis." In this sense, then, scientific facilitation may be regarded as an aspect of scientific leadership (Durose et al., 2021; Eigenbrode et al., 2017; Sapienza, 2004) that is necessary for producing knowledge, addressing power dynamics, and making space for the voices and contributions of diverse collaborators of all ages, stages, and backgrounds (Bens, 2017; Carpenter-Song and Whitley, 2013; Gaughan and Bozeman, 2016). Science facilitation expertise and the techniques used by skilled practitioners connect to and to some extent overlap with other domains, including project management (Sutton et al., 2019), organisational behaviour (Champoux, 2016), and conflict resolution (Carpenter and Kennedy, 2001; Rosenberg, 2012). However, we argue that the heart of science facilitation expertise is distinct, shaped by the unique sets of past experiences and metacognitive learning science facilitators bring to their roles. We thus offer four recommendations to increase the capacity of individual scientists, teams, institutions, and the wider scientific community to access this essential skill.

First, making access to science facilitation expertise more widespread will require support from funders. Science facilitation requires a specialised set of skills, training, and experience. At the individual project level, PIs need to make sure budget requests realistically reflect the facilitation needs of their teams, whether they are asking for professional development for a Path 1 facilitator or support for a Path 2 or 3 facilitator. While requesting funding for facilitation may still seem unorthodox within some contexts, funding agencies around the world are increasingly requiring clear descriptions of how researchers will manage projects and how interdisciplinary teams will ensure collaboration is successful (e.g., Dynamics of Integrated Socio-Environmental Systems (DISES), 2020; Marsden Fund Council, 2021). Budgeting in a facilitator can fit naturally within these guidelines. At the level of the research programme or funding agency, widespread anecdotal evidence and qualitative studies of individual projects (e.g., Love et al., 2021) suggests the return on investment for funding science facilitation is likely to be high, though this is an area ripe for further empirical evaluation. In the meantime, we suggest that funders remain open to paying for facilitation training for scientists or external facilitation, particularly for large or complex interdisciplinary projects.

Second, the process of science facilitation takes time and preparation (Graef et al., 2021), primarily because the collaborative and breakthrough science processes that are being guided require substantial time, effort, preparation, and trust among participants to succeed (National Research Council (NRC), 2015). A rule of thumb one of our author team uses is that every hour of quality meeting time will take two to three hours of planning time; there is also time needed for PI(s) and science facilitator to get on the same page. This means an external facilitator can most effectively aid a team when they are brought into a process early and allowed sufficient time to do their job. Depending on the team and project, timing can be an additional reason that a Path 1 facilitator is the right choice, as their dual role means they are by definition on the same timeline as the team.

Third, we urge research institutions, funding agencies, and those who educate scientists to consider how scientific facilitation expertise might be cultivated within scientists' career trajectories, as well as within the scientific workforce. We find scientific communication to be an instructive analogue. Science communication has become widely recognised as a skill set that all scientists should develop to ensure their research findings are understood and useful to key audiences (Burns et al., 2003; Fischhoff, 2019). In a world where science is increasingly done in collaborative teams, we propose that science facilitation needs to be recognised as a core expertise deserving similar investment. Even if scientific teams rely on external science facilitators, PIs and team leaders need to be able to collaborate effectively with the facilitators they hire. Furthermore, some of the graduate students of today might be the science facilitators of tomorrow.

We argue that a range of professional development opportunities at a range of experience levels ought to be available. Instead, when members of our author team searched recently for such specialised training, we found almost nothing focused specifically on science facilitation, though introductory (general) facilitation courses are widely available through universities and non-profits. Like many other interactional forms of expertise, science facilitation capability is gained through practical experience and metacognition, suggesting the need to develop training opportunities that support learning from a person's early facilitation attempts, especially those within a science context. At present, scientists who are interested in facilitation may look to established facilitation societies (e.g., International Association of Facilitators (IAF)) for workshops, guidelines, and other resources related to facilitation skills. Scientists can also seek out facilitation mentors who may be willing to let them apprentice as a co-facilitator during meetings or serve as a coach to aid reflective learning as one gains experience.

Finally, there is a need to take the conceptual arguments presented here and move them the next step forward into implementation. One need is to assess where to situate scientific facilitation expertise within scientific institutions. Faculty members and other research personnel frequently use facilitation skills when convening and leading team science projects, though few have received training for this aspect of their roles. For larger programmes or cross-institutional initiatives, there are already roles such as project managers, programme managers, and research coordinators who likely already use scientific facilitation skills but may not be recognised for it. Within universities, staff in research development offices, interdisciplinary research centres, and centres for teaching and learning may play important roles in the development of new projects, in project implementation, or evaluation. In some cases, these types of centres or offices are investing in team science or interdisciplinary research positions that require significant science facilitation expertise. Faculty, programme managers and university staff who facilitate scientific teams may desire additional opportunities to hone their skills, especially if they never received explicit facilitation training. Additionally, there is a small but growing number of private firms offering science facilitation consulting.

A second need is to analyse when in the scientific pipeline facilitation support might be most essential. The authors' experience with seed funding opportunities offered by the NSF and other organisations that provide support (e.g., time, training, education, and financial resources) for teams to brainstorm, develop, and prepare for larger grant proposals suggests that the project scoping phase might be a particularly fruitful time for facilitation, as this is when diverse team members' assumptions about research, understandings of key science needs, and individual interests are melded into a compelling collective proposal. Other initiation activities (e.g., starting a new research centre, kicking off a working group, welcoming a new cohort of graduate students into a multi-institution project) might similarly warrant facilitation assistance.

Breakthrough science that can address society's most pressing problems is, and will continue to be, an essential branch of science. Science facilitation shows great promise as a strategy for supporting collaborative teams to conduct breakthrough science (Graef et al., 2021), but remains underexplored and underrecognized. The last decades have seen an explosion of professional development focused on science communication, driven by a shared recognition that science communication is a foundational scientific practice requiring specific expertise (Burns et al., 2003; Fischhoff, 2019). We hope that in the years to come, science facilitation will similarly come to be recognised as foundational to the collaborative generation of cutting-edge, solutions-focused scientific knowledge.

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References

Arnott JC, Mach KJ, Wong-Parodi G (2020) Editorial overview: the science of actionable knowledge. Curr Opin Environ Sustain 42:A1–A5. https://doi.org/10.1016/j.cosust.2020.03.007

Bammer G (2013) Disciplining interdisciplinary: integration and implementation sciences for researching complex real-world problems. The Australian National University Press, Canberra

Bammer G (2017) Should we discipline interdisciplinarity? Palgrave Commun 3(1):30. https://doi.org/10.1057/s41599-017-0039-7

Bammer G, O'Rourke M, O'Connell D, Neuhauser L, Midgley G, Klein JT, Grigg NJ, Gadlin H, Elsum IR, Bursztyn M, Fulton EA, Pohl C, Smithson M, Vilsmaier U, Bergmann M, Jaeger J, Merkx F, Vienni Baptista B, Burgman MA, Walker DH, Young J, Bradbury H, Crawford L, Haryanto B, Pachanee CA, Polk M, Richardson GP (2020) Expertise in research integration and implementation for tackling complex problems: when is it needed, where can it be found and how can it be strengthened? Palgrave Commun 6(1):5. https://doi.org/10.1057/s41599-019-0380-0

Barge JK, Shockley-Zalabak P (2008) Engaged scholarship and the creation of useful organizational knowledge. J Appl Commun Res 36:251–265. https://doi.org/10.1080/00909880802172277

Bennett LM, Gadlin H, Levine-Finley S (2010) Collaboration and team Science field guide. National Institutes of Health, Publication No. 18–7660. https://www.cancer.gov/about-nci/organization/crs/research-initiatives/team-science-field-guide/collaboration-team-science-guide.pdf

Bens I (2017) Facilitating with Ease!: core skills for facilitators, team leaders and members, managers, consultants, and trainers. John Wiley & Sons, Hoboken, NJ

Boix Mansilla V, Lamont M, Sato K (2016) Shared cognitive–emotional–interactional platforms: markers and conditions for successful interdisciplinary collaborations. Sci Technol Hum Values 41:571–612. https://doi.org/10.1177/0162243915614103

Bozeman B, Fay D, Slade CP (2013) Research collaboration in universities and academic entrepreneurship: the-state-of-the-art. J Technol Transf 38:1–67. https://doi.org/10.1007/s10961-012-9281-8

Bunker BB, Alban BT (2012) The handbook of large group methods: creating systemic change in organizations and communities. Jossey-Bass, San Francisco

Burns TW, O'Connor DJ, Stocklmayer SM (2003) Science communication: a contemporary definition. Public Underst Sci 12(2):183–202. https://doi.org/10.1177/09636625030122004

Carcasson M, Sprain L (2016) Beyond problem solving: reconceptualizing the work of public deliberation as deliberative inquiry. Commun Theory 26(1):41–63. https://doi.org/10.1111/comt.12055

Carpenter-Song E, Whitley R (2013) Behind the scenes of a research and training collaboration: power, privilege, and the hidden transcript of race. Cult Med Psychiatry 37(2):288–306. https://doi.org/10.1007/s11013-013-9311-5

CarpenterSL, Kennedy, WJ (2001) Managing public disputes: a practical guide to handling conflict and reaching agreements. Jossey-Bass, San Francisco

Champoux JE (2016) Organizational behavior: integrating individuals, groups, and organizations, 5th edn. Routledge, New York

Chrislip DD, Larson CE (1994) Collaborative leadership: how citizens and civic leaders can make a difference. Jossey-Bass, San Francisco

Clark TR (2020) The 4 stages of psychological safety: defining the path to inclusion and innovation. Berrett-Koehler Publishers, Oakland, CA

Collins H, Evans R (2007) Rethinking expertise. Chicago UP, Chicago

Csikszentmihalyi M (1998) Finding flow: the psychology of engagement with everyday life. Basic Books, New York

De Montjoye YA, Stopczynski A, Shmueli E, Pentland A, Lehmann S (2014) The strength of the strongest ties in collaborative problem solving. Sci Rep 4. https://doi.org/10.1038/srep05277

de Vos Malan J (2016) Invited Editorial: transdisciplinary research management: the case for specialised skills. Eur Sci J 12(25):1. https://doi.org/10.19044/esj.2016.v12n25p1

Dilling L, Lemos MC (2011) Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. Global Environ Change 21(2):680–689. https://doi.org/10.1016/j.gloenvcha.2010.11.006

Duhigg C (2016). What Google learned from its quest to build the perfect team. N Y Times Mag. https://www.nytimes.com/2016/02/28/magazine/what-google-learned-from-its-quest-to-build-the-perfect-team.html. Accessed 21 Dec 2021

Durose C, Perry B, Richardson L, Dean R (2021) Leadership and the hidden politics of co-produced research: a Q-methodology study. Dig Int J Soc Res Methodol 1–21 https://doi.org/10.1080/13645579.2021.1960738

Dynamics of Integrated Socio-Environmental Systems (DISES) (2020) Program solicitation: NSF 20-579. https://www.nsf.gov/pubs/2020/nsf20579/nsf20579.htm. Accessed 21 Dec 2021

Edmondson A (1999) Psychological safety and learning behavior in work teams. Adm Sci Q 44(2):350–383. https://doi.org/10.2307/2666999

Eigenbrode SD, Martin T, Morton LW, Colletti J, Goodwin P, Gustafson R, Hawthorne D, Johnson A, Klein JT, Mercado L, Pearl S, Richard T, Wolcott M (2017) Leading large transdisciplinary projects addressing social ecological systems: a primer for project directors. U.S. Department of Agriculture, National Institute of Food and Agriculture. https://nifa.usda.gov/leading-transdisciplinary-projects

Fiore SM (2008) Interdisciplinarity as teamwork. Small Gr Res 39:251–277. https://doi.org/10.1177/1046496408317797

Fischhoff B (2019) Evaluating science communication. Proc Natl Acad Sci USA 116(16):7670. https://doi.org/10.1073/pnas.1805863115

Fisher R, Ury W, Patton B (2011) Getting to yes: negotiating agreement without giving in. Penguin, New York

Gadlin H, Jessar K (2002). Preempting discord: prenuptial agreements for scientists. US Department of Health & Human Services. https://ori.hhs.gov/preempting-discord-prenuptial-agreements-scientists. Accessed 21 Dec 2021

Gaughan M, Bozeman B (2016) Using the prisms of gender and rank to interpret research collaboration power dynamics. Soc Stud Sci 46(4):536–558. https://doi.org/10.1177/0306312716652249

Graef DJ, Kramer JG, Motzer N (2021) Facilitating interdisciplinary meetings: a practical guide. National Socio-Environmental Synthesis Center. https://www.sesync.org/document-facilitating-interdisciplinary-meetings-a-practical-guide

Graef DJ, Motzer N, Kramer JG (2021) The value of facilitation in interdisciplinary socio-environmental team research. Socio-Ecol Pract Res 3(2):109–113. https://doi.org/10.1007/s42532-021-00082-7

Grippin P, Peters S (1984) Learning theory and learning outcomes: the connection. University Press of America, Lanham, MD

Hall KL, Vogel AL, Huang GC, Serrano KJ, Rice EL, Tsakraklides SP, Fiore SM (2018) The science of team science: a review of the empirical evidence and research gaps on collaboration in science. Am Psychol 73:532–548. https://doi.org/10.1037/amp0000319

Hall KL, Vogel AL, Stipelman BA, Stokols D, Morgan G, Gehlert S (2012) A four-phase model of transdisciplinary team-based research: goals, team processes, and strategies. Transl Behav Med 2(4):415–430. https://doi.org/10.1007/s13142-012-0167-y

Halpern M, O'Rourke M (2020) Power in science communication collaborations. J Sci Commun 19(4):C02. https://doi.org/10.22323/2.19040302

Harvey M, Coulson D, McMaugh A (2016) Towards a theory of the ecology of reflection: Reflective practice for experiential learning in higher education. J Univ Teach Learn Pract 13(2):2, http://www.scopus.com/inward/record.url?scp=84969849779&partnerID=8YFLogxK

Hogan C (2005) Understanding facilitation: theory and principle. Kogan Page Publishers, London

Hubbs G, O'Rourke M, Orzack SH (2020) The Toolbox dialogue initiative: the power of cross-disciplinary practice. CRC Press, Boca Raton, FL

Hunter D (2009) The art of facilitation: the essentials for leading great meetings and creating group synergy. Jossey-Bass, San Francisco

International Committee of Medical Journal Editors (ICMJE) (2021) Defining the role of authors and contributors. International Committee of Medical Journal Editors. http://www.icmje.org/recommendations/browse/roles-and-responsibilities/defining-the-role-of-authors-and-contributors.html. Accessed 21 Dec 2021

Johns CE (2017) Becoming a reflective practitioner, 5th edn. John Wiley & Sons, Hoboken, NJ

Jones BF, Wuchty S, Uzzi B (2008) Multi-university research teams: Shifting impact, geography, and stratification in science. Science 322(5905):1259–1262. https://doi.org/10.1126/science.1158357

Kaner S (2014) Facilitator's guide to participatory decision-making, 3rd edn. Jossey-Bass, San Francisco

Khagram S, Nicholas KA, Bever DM, Warren J, Richards EH, Oleson K, Kitzes J, Katz R, Hwang R, Goldman R, Funk J, Brauman KA (2010) Thinking about knowing: conceptual foundations for interdisciplinary environmental research. Environ Conserv 37(4):388–397. https://doi.org/10.1017/S0376892910000809

Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P, Swilling M, Thomas CJ (2012) Transdisciplinary research in sustainability science: Practice, principles, and challenges. Sustain Sci 7(1):25–43. https://doi.org/10.1007/s11625-011-0149-x

Lencioni P (2002) The five dysfunctions of a team. Jossey-Bass, San Francisco.

Love HB, Cross JE, Fosdick B, Crooks KR, VandeWoude S, Fisher ER(2021) Interpersonal relationships drive successful team science: an exemplary case-based study Humanii Soc Sci Commun 8(1):1–10. https://doi.org/10.1057/s41599-021-00789-8

Marsden Fund Council (2021) Marsden Fund Council Award guidelines for applicants. Marsden Fund. https://www.royalsociety.org.nz/what-we-do/funds-and-opportunities/marsden/marsden-fund-application-process/submitting-a-proposal/marsden-fund-council-award-guidelines-for-applicants/ Accessed 21 Dec 2021

Matthews NE, Cizauskas CA, Layton DS, Stamford L, Shapira P (2019) Collaborating constructively for sustainable biotechnology. Sci Rep 9:19033. https://doi.org/10.1038/s41598-019-54331-7

Means JA, Adams T (2005) Facilitating the project lifecycle: the skills & tools to accelerate progress for project managers, facilitators, and six sigma project teams. Jossey-Bass, San Francisco

Moon K, Blackman DA, Adams VM, Colvin RM, Davila F, Evans MC, Januchowski-Hartley SR, Bennett NJ, Dickinson H, Sandbrook C, Sherren K, St. John FAV, van Kerkhoff L, Wyborn C (2019) Expanding the role of social science in conservation through an engagement with philosophy, methodology, and methods. Methods Ecol Evol 10(3):294–302. https://doi.org/10.1111/2041-210X.13126

Morisette JT, Cravens AE, Miller BW, Talbert M, Talbert C, Jarnevich C, Fink M, Decker K, Odell EA (2017) Crossing boundaries in a collaborative modeling workspace. Soc Nat Resour 30(9):1158–1167. https://doi.org/10.1080/08941920.2017.1290178

National Research Council (NRC) (2015) Enhancing the Effectiveness of Team Science. The National Academies Press, Washington, DC

National Science Foundation (NSF) (2017) Growing Convergence Research at NSF. National Science Foundation Report 17-065. https://beta.nsf.gov/funding/opportunities/growing-convergence-research-nsf

National Science Foundation (NSF) (2022) Convergence research at NSF. https://www.nsf.gov/od/oia/convergence/index.jsp. Accessed 1 Apr 2022

O'Rourke M, Crowley SJ (2013) Philosophical intervention and cross-disciplinary science: The story of the Toolbox Project. Synthese 190:1937–1954. https://doi.org/10.1007/s11229-012-0175-y

Ormrod JE (2016) Human Learning, 7th edn. Pearson Higher Ed, Hoboken, NJ

Parker P (2020) The art of gathering: How we meet and why it matters. Riverhead Books, New York

Penn State Clinical and Translational Science Institute (2021) Team science toolbox: Team launch. Penn State College of Medicine. https://ctsi.psu.edu/research-support/team-science-toolbox/launch/. Accessed 21 Dec 2021

Phelps C, Heidl R, Wadhwa A, Paris H (2012) Agenda knowledge, networks, and knowledge networks: a review and research. J Manag 38:1115–1166. https://doi.org/10.1177/0149206311432640

Read EK, O'Rourke M, Hong GS, Hanson PC, Winslow LA, Crowley S, Brewer CA, Weathers KC (2016) Building the team for team science. Ecosphere 7:e01291. https://doi.org/10.1002/ecs2.1291

Rittel HW, Webber MM (1973) Dilemmas in a general theory of planning. Policy Sci 4(2):155–169. https://doi.org/10.1007/BF01405730

Rosenberg M (2012) Living nonviolent communication: Practical tools to connect and communicate skillfully in every situation. Sounds True, Boulder, CO.

Salazar MR, Lant TK, Fiore SM, Salas E (2012) Facilitating innovation in diverse science teams through integrative capacity. Small Gr Res 43:527–558. https://doi.org/10.1177/1046496412453622

Sapienza AM (2004) Managing Scientists: leadership strategies in scientific research. John Wiley & Sons

Sawyer RK (2003) Emergence in creativity and development. Oxford UP, Oxford.

Schiermeier Q (2021) How Europe's €100-billion science fund will shape 7 years of research. *Nature* 591:20–21 https://doi.org/10.1038/d41586-021-00496-z

Schön DA (1983) The reflective practitioner: How professionals think in action. Basic Books, New York

Schön DA (1987) Educating the reflective practitioner. Basic Books, New York.

Schuman Se (2005) The IAF handbook of group facilitation: best practices from the leading organization in facilitation, vol. 1. Jossey-Bass, San Francisco

Stokols D, Hall KL, Taylor BK, Moser RP (2008) The science of team science: overview of the field and introduction to the supplement. Am J Prev Med 35(2):S77–S89. https://doi.org/10.1016/j.amepre.2008.05.002
Strober M (2010) Interdisciplinary conversations: challenging habits of thought. Stanford UP, Stanford
Sutton L, Berdan LG, Bolte J, Califf RM, Ginsburg GS, Li JS, McCall J, Moen R, Myers BS, Rodriquez V, Veldman T, Boulware LE (2019) Facilitating translational team science: the project leader model. J Clin Transl Sci 3(4):140–146. https://doi.org/10.1017/cts.2019.398
Tabaka J (2006) Collaboration explained: facilitation skills for software project leaders. Pearson Education, Upper Saddle River, NJ
Tuckman BW (1965) Developmental sequence in small groups. Psychol Bull 63(6):384–389. https://doi.org/10.1037/h0022100
Ulibarri N, Cravens AE, Nabergoj AS, Kernbach S, Royalty A (2019) Creativity in research. Cambridge University Press, Cambridge, UK
Wardale D (2013) Towards a model of effective group facilitation. Leadersh Organ Dev J 34(2):112–129. https://doi.org/10.1108/01437731311321896
Woolf SH (2008) The meaning of translational research and why it matters. JAMA 299(2):211–213
Wróbel AE, Lomberg C, Cash P (2021) Facilitating design: examining the effects of facilitator's neutrality on trust and potency in an exploratory experimental study. Des Sci 7(e6):Article e6. https://doi.org/10.1017/dsj.2021.5
Zhang HH, Ding C, Schutte NS, Li R (2020) How team emotional intelligence connects to task performance: a network approach. Small Group Res 51:492–516. https://doi.org/10.1177/1046496419889660
Zhang J, Scardamalia M, Reeve R, Messina R (2009) Designs for collective cognitive responsibility in knowledge-building communities. J Learn Scs 18:7–44. https://doi.org/10.1080/10508400802581676

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All authors (AEC, MSJ, CN, JZ, and HBL) jointly conceptualised the study, developed the ideas, wrote the paper, and revised and edited the paper. AEC and CN created the visualisations.

Competing interests

AEC, MSJ, CN, JZ, and HBL declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

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Additional information

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