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A model for principals' STEM leadership capability

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Abstract

In this paper we develop a model for the capabilities required by principals for effective Science, Technology, Engineering and Mathematics (STEM) leadership. The model underpinned a large national cross-sectional research and development project across Australian states in both primary and secondary schools. This model is developed via synthesis of research literature across leadership and STEM education. The model consists of five dimensions of principals' STEM capability: (1) STEM discipline-specific and integrated knowledge and practices; (2) contexts; (3) dispositions; (4) tools; and (5) critical orientation. These dimensions represent distinct, but interrelated, capacities required by principals to establish and maintain positive STEM learning cultures within schools. Elaborations have been provided, in the form of capabilities, for each of these dimensions. The model has the potential for shaping principals' STEM leadership development trajectories and structuring targeted professional learning programmes for principals, teachers and other members of the school community.

KEYWORDS

capability, leadership, principals, STEM

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Key insights

what is the main issue that the paper address?

The paper is concerned with the need to identify the leadership capabilities required by principals to develop positive Science, Technology, Engineering and Mathematics education cultures within their schools.

What are the main insights the paper provides?

The paper provides a model for the capabilities required by principals for effective Science, Technology, Engineering and Mathematics (STEM) leadership. The model has the potential to inform approaches to the development of positive school cultures in STEM and structure principals' STEM leadership development trajectories.

INTRODUCTION

Improving the quality of Science, Technology, Engineering and Mathematics (STEM) education has been a goal of governments, policy makers, education systems and schools across the globe for at least the past decade (e.g., Charette, 2013; Geiger, 2019). The reasons for this increased focus on STEM education can be categorised into two broad areas: (1) the need to develop a STEM-capable workforce—seen as the foundation for the innovation required to generate future economic prosperity (e.g., European Parliament, 2015; Honey et al., 2014; Hopkins et al., 2014; Marginson et al., 2013); and (2) the promotion of STEM literacy as a key capability for informed, participating and contributing citizenship (e.g., Bybee, 2010; Charette, 2013; Zollman, 2012). The need to enhance approaches to STEM education has been further highlighted in recent times because of the impact of the global COVID-19 pandemic and the growing awareness of other disruptive events such as global warming, food and energy security and economic instability. Such events act as reminders of the role STEM education should play in responsible and critical citizenship (e.g., Maass et al., 2019a) and for addressing pressing social challenges (e.g., Lee & Grapin, 2022). Maass et al. (2019b) argue that projects such as the European project MaSDiV, that links citizenship education to STEM teaching (https://icse.eu/international-projects/masdiv/), are key ‘if young people, as they move into adulthood, are to be equipped to make the moral and ethical decisions and judgements needed to ensure a sustainable, equitable and peaceful transition to a world of rapid technological, social and economic change’ (p. 875). Thus, STEM education is seen as essential for the development of responses to current and anticipated future challenges associated with a world characterised by rapid technological, economic and social change (Maass et al., 2019b).

While national policy documents and research literature in education highlight the need for a STEM-capable workforce and a STEM-literate citizenry, graduation rates in many countries are not meeting current or projected demand within the STEM disciplines (Hossain & Robinson, 2012; Office of the Chief Scientist Australia, 2014), and may even be in decline in some countries (e.g., Wienk, 2017). These concerns and potential strategies for addressing this situation were brought together in Australia's *National STEM school education strategy* (Education Council, 2015). Government-funded initiatives in response to recommendations from this and other documents (e.g., Australian Government, 2016) include initiatives aimed at: enhancing the discipline content knowledge of initial teacher education students (e.g., Mulligan et al., 2017); enhancing classroom teaching practices

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specific to STEM (e.g., Hobbs et al., 2018); developing partnerships between STEM professionals and schools (CSIRO, 2020); and the development of STEM teaching/learning resources (Hatisaru et al., 2021). While each of these initiatives have reported successful specific outcomes, to date, there appears to have been little progress against the broader aspirations of the *National STEM school education strategy* (Education Council, 2015), such as: increasing school students' aspirations towards STEM careers and engagement with STEM subjects at school; or university enrolments in relevant STEM disciplines in the longer term (e.g., Anderson, 2020; Bennett et al., 2021; Marginson et al., 2013; Timms et al., 2018). This lack of progress suggests that current strategies are not sufficient to achieve noteworthy change. This situation is reflected across international contexts (e.g., Regan & DeWitt, 2015).

Principals have been identified as key figures in realising the potential of whole-school approaches to educational change (e.g., Pietsch & Tulowitzki, 2017; Robinson, 2007), yet, while there are studies and policy documents that have described frameworks for the STEM capabilities of students (e.g., Delahunty & Kimbell, 2021) and teachers (e.g., Australian Government, 2021), there is relatively limited research into the role of school leaders in improving STEM education (Likourezos et al., 2020; Wenner, 2017). Further, currently available literature has tended to draw on general themes associated with instructional leadership (e.g., Aas & Paulsen, 2019) rather than the specific capabilities necessary for principals to be effective STEM education leaders. Similarly, there is no clear advice on the content and structure of professional learning programmes needed to support the development of principals' STEM education capabilities. In this paper we respond to this theory/practice gap by addressing the following research question: *What capabilities are required by principals to undertake effective STEM leadership in their schools?*

This question was the focus of a national research project—Principals as STEM Leaders (PASL)—which involved 104 principals and their schools across all educational sectors and states in Australia. Project activity was underpinned by a model grounded in the capabilities principals require for effective STEM leadership, generated as a synthesis of relevant research literature. We make use of the term 'capabilities' rather than 'competencies' deliberately, consistent with the perspective of Blaschke and Hase (2016) as the 'capacity to use one's competence in novel as well as familiar circumstances' (p. 26). In this instance, effective school leadership is tied closely to how principals use what they know to promote the goals of education in their schools within ever-changing circumstances. This model is based on a synthesis of research literature across leadership and STEM education research, to extend a model for the cross-curriculum implementation of numeracy programmes (Goos et al., 2014). In addition to describing the capabilities required of principals to lead STEM education in their schools, the model provides a structure for the development of professional learning programmes in STEM education leadership. The model has been endorsed by principals through work conducted during workshops throughout the project. This involved scrutiny of an initial version of the model by principals and cycles of revision based on their advice. While the empirical validation of the model is the subject of a manuscript under development, in this paper we present the theoretical underpinnings of the model.

In describing the model, we first outline the notion of *capability*. Second, we present a discussion of current research and practices in STEM education. Third, we describe the Model of Numeracy for the 21st Century (Goos et al., 2014) as a starting point for defining the dimensions of STEM leadership capability. Fourth, we outline and explain the dimensions of the model for STEM leadership capability. Finally, we discuss the implications of the model for theory and practice in STEM education.

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CURRENT RESEARCH AND PRACTICES IN CAPABILITIES/COMPETENCIES

Principals' STEM capability must accommodate demands beyond those of competence. In education, competence has traditionally been used in vocational education and training. Competency-based approaches in these contexts tend to be highly structured and teacher-centred. Although both terms refer to a capacity to perform a task or role, capability is a broader concept that goes beyond specific well-defined skills. Capability refers to the use of an amalgam of knowledge, skills and personal qualities that allow effective responses in novel and changing circumstances rather than only in familiar contexts and in relation to familiar or routine problems (Stephenson & Yorke, 2012). School principals lead in environments that are constantly changing and uncertain (Jensen et al., 2017) and so capability rather than merely competence is required. Nevertheless, we use the term ‘competency’ when referring to relevant work in which cited authors employ it, essentially synonymously, with our definition of capability.

Competency is widely considered to encompass the cognitive, technical, integrative, contextual, relational, moral and self-regulatory attributes necessary to successfully fulfil the requirements of a role within personal, civic and work life (Epstein & Hundert, 2002). Weinert (2001) suggested that competency can be acquired through experience, for example, exposure to situations, or through formal training and qualification.

Individuals, such as school leaders, enact capability in their professional context. Frameworks that identify school leadership competencies have been developed by education systems throughout the world (e.g., Saleniece et al., 2019; Suharyati & Laihad, 2020; Viscera & Maico, 2019; Weiler & Hinnant-Crawford, 2021). For example, the *Australian professional standard for principals and leadership profiles* (AITSL, 2014) identifies competencies-in-action based on core leadership practices and behaviours specific to school contexts, such as instructional leadership. Consistent with the view that leadership competency can be appropriated (e.g., Klieme et al., 2008; Weinert, 2001), the AITSL (2014) standards were developed from the stance that competency can be developed, and expert principals are those who consistently work to develop both themselves and others.

The model of STEM leadership capability that we present here includes, in relation to STEM leadership, each of the aspects of Stephenson and Yorke's (2012) conceptualisation of capability. We explicitly unpack the knowledge and skills required along with requisite personal qualities, framed as dispositions, that contribute to STEM leadership capability. We also acknowledge the need for principals to lead in dynamic contexts that are characterised by competing demands and opportunities. Making decisions and building and maintaining a positive STEM culture in such contexts demands a critical orientation that draws upon diverse data, extensive knowledge and highly developed skills to make appropriate decisions. Such an orientation is implicit in notions of capability described in the literature (e.g., Stephenson & Yorke, 2012) and central to our model of STEM leadership capability.

RESEARCH ACROSS STEM EDUCATION AND ITS PRACTICES

The use of the term ‘STEM education’ is now widespread (Bybee, 2013). Agreement about the ways in which individual disciplines are interrelated and how STEM is enacted in educational settings, however, is currently a matter of contention (e.g., English, 2017; Martín-Páez et al., 2019). The broad focus of STEM adds further complexity to research in STEM education as this includes: the creation of models that guide thinking about the purposes and outcomes of STEM education (e.g., Honey et al., 2014); teacher understandings of STEM

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integration (e.g., Margot & Kettler, 2019); teachers' perspectives on STEM learning environments (e.g., Hatisaru et al., 2020); the ways in which STEM teaching is implemented in schools (e.g., Thibaut et al., 2018); factors that influence who succeeds (or not) in STEM (e.g., Wieselmann et al., 2020); challenges associated with the assessment of STEM learning (e.g., Fang & Hsu, 2019); and the link between STEM, educational interventions and student outcomes (e.g., Yildirim, 2016). Research in this area is ongoing, with a recent systematic analysis of research and trends in STEM education journal publications (Li et al., 2020) indicating that STEM education research is increasing in importance internationally.

Despite its increasing importance, inconsistencies in operational definitions and related terminology (Dare et al., 2019) have hampered research in STEM education. The acronym STEM itself, for example, is used in different ways within schooling, such as: (i) a model of implementation; (ii) a set of instructional practices; (iii) an area of study; and (iv) a career (Hasanah, 2020). STEM education is also understood in different ways as it can be seen to focus on addressing authentic problems (Honey et al., 2014) through both the teaching of the individual curriculum areas (science, digital and design technologies and mathematics) and the integration of two or more of its constituent disciplines (Hobbs et al., 2018). Vasquez et al. (2013) recognised these different perspectives by referring to a continuum of STEM education that ranges between a singular disciplinary focus (concepts and skills learnt separately in each discipline) and transdisciplinary approaches that integrate one or more disciplines when addressing real-world problems.

The implementation of STEM education programmes in schools has proved challenging. In a metasynthesis of research on interdisciplinary STEM education, Yildirim (2016) noted that a major impediment was that many teachers did not have sufficient knowledge in, and experience with, STEM education, nor were they skilled at integrating the individual STEM disciplines in a meaningful way. Barriers to the development of these capabilities have been identified by Shernoff et al. (2017), including understanding the nature of integrated STEM and sufficient depth of content knowledge within and across STEM disciplines. Further, implementing integrated STEM education requires teachers and school leaders to have a knowledge of and capacity to adopt a range of student-centred pedagogical practices and innovative assessment strategies. Adopting these approaches can represent a challenge for some teachers, who are also expected to deliver rigorous instruction in mathematics and science while, at the same time, supporting students to apply this knowledge to a scenario in engineering, for example, that requires the use of technology to find a solution (Hollman et al., 2019; Kennedy et al., 2014). In such learning environments, instruction and assessment become carefully articulated or even intertwined (e.g., Capraro & Corlu, 2013) as students develop creative solutions to real-world problems within collaborative, self-regulated learning environments (Fang & Hsu, 2019). While multilevel/multifaceted STEM assessment frameworks are being developed (Arikan et al., 2020; Fang & Hsu, 2019), more research is needed to investigate how, and to what extent, STEM learning can 'cultivate students' development of inquiry abilities, higher-order thinking skills or creativity' (Fang & Hsu, 2019, p. 201). Teachers' attempts to develop the necessary instructional capabilities in STEM are further compromised by a lack of preparation time, rigid school structures and organisation, a lack of relevant resources, teacher professional learning (pre- and in-service) and validated models of STEM education instruction and assessment. These findings highlight the importance of teachers' disciplinary and interdisciplinary knowledge in the implementation of STEM education, which also has implications for those providing STEM leadership in schools.

The need to develop capability with both disciplinary and interdisciplinary knowledge is connected directly to the focus of STEM on solving real-world problems. To be relevant to teachers and students, such problems are best connected to contexts that are compelling, interesting or motivating—such as global events (e.g., Gal & Geiger, 2022 [COVID-19 pandemic]) or issues related to specific school environments (e.g., Bolman & Deal, 2017;

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Thibaut et al., 2018 [local Landcare projects]). In such contexts, students participate in inquiry-based learning, reasoning, problem-solving and the development of creativity through immersion in real-world settings (Kelley & Knowles, 2016; Kennedy & Odell, 2014; McDonald, 2016). To connect learning to such contexts, school leaders and teachers must not only be aware of events in the broader world that have global impact, but also be able to take advantage of developments within local school communities. At the same time, given the challenges associated with the implementation of STEM programmes in schools, Watters and Diezmann (2013) have argued that there is a need to assess the demands placed on teachers by schools when embracing community partnerships, in addition to the responsibility for student learning outcomes, including career pathways.

Yildirim (2016) also identified potential impacts on student learning, including impediments to positive achievement outcomes. This study found that there was potential: for students to realise deeper learning and academic success; for improved attitudes towards learning, interest in and motivation to study STEM subjects; and to promote creative thinking, problem-solving and scientific process skills. Others have found, however, that these gains are dependent on leaders' and teachers' dispositions and beliefs in relation to STEM education. These include a disposition to be involved in innovation practices (e.g., Davis et al., 2019) and promote change (e.g., Rogers, 2007). The development of STEM capability also requires a belief that all members of a school community can aquire and contribute to an understanding of STEM and its practices (e.g., Beswick & Jones, 2011; Jeffries et al., 2019), a position that is particularly important when catering for diverse learners (Margot & Kettler, 2019).

A lack of empirical evidence is also an obstacle to the implementation of research-based STEM educational resources such as those advocated by Rosicka (2016), who argues that these must be suitable and/or adaptable for the needs of all learners including teachers (Margot & Kettler, 2019). The use of STEM resources, including tools such as computers and other physical or digital tools (e.g., force detectors), requires informed selection as well as support for using them effectively (e.g., Hollman et al., 2019; Kennedy et al., 2014).

Critical thinking focused on finding solutions to real-world problems is central to STEM education. Such critical thinking requires the evaluation of evidence when forming judgements or making decisions—a critical orientation (see, e.g., Gómez & Suárez, 2020; Goos et al., 2014). At the same time, the development and implementation of tasks that require students to exercise critical capabilities is a capacity that teachers find challenging (e.g., Geiger, 2019). Despite this challenge, the development of effective teaching practices that embrace a critical orientation to teaching and learning has been shown to be possible where effective models for planning are provided and sufficient school support is available to acquire the necessary task design and instructional capabitities (e.g., Goos et al., 2020). In providing the relevant support, school leaders themselves must be aware of the critical demands associated with implementing STEM education programmes and be capable of fostering the teacher capacity-building necessary to bring about this type of educational change (Branson et al., 2018).

While there have been positive reports on the outcomes of integrated STEM initiatives (e.g., Hobbs et al., 2018), there are relatively few longitudinal evaluation reports on the implementation of STEM programmes—a situation aggravated by funding within STEM that tends to be focused on single disciplines (e.g., Li et al., 2020). Of those programmes that claim successful outcomes, factors that seem key are interdisciplinary collaboration and the sharing of knowledge between and across faculties/departments (e.g., Lane et al., 2022; Li, 2020; Wang et al., 2020), positive teachers' dispositions and beliefs (Dong et al., 2020; El Nagdi et al., 2018; Goos et al., 2020), the provision of time and support for the acquisition of new capabilities (e.g., with digital tools) (Hollman et al., 2019; Kennedy et al., 2014)—all necessary for teachers and students to develop integrated STEM identities (e.g., Galanti

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& Holincheck, 2022). The lack of longitudinal data about students' attainment of relevant knowledge, understanding, skills, values, attitudes, engagement and participation following STEM interventions is compounded by limited research into the influence of teacher attitudes and school context on the implementation of STEM integration (Hudson et al., 2015; Thibaut et al., 2018) and challenges associated with the assessment of student learning in interdisciplinary STEM education (Gao et al., 2020), making it difficult to draw valid conclusions (Chachashvili-Bolotin et al., 2016).

Key to addressing the challenges associated with integrated STEM learning is 'systematic and joined-up policies' (Timms et al., 2018, p. 25), enacted by principals who recognise and reward teachers' efforts to integrate STEM, particularly when conducted in collaboration with external stakeholders (Kennedy & Odell, 2014). This observation identified the key role of leadership in integrated STEM education and how they enact principles of organisational learning (López et al., 2022), which are needed to manage the expectation of school systems, coordinate the efforts of teachers, ensure quality learning outcomes for all students and harness the support of the school community.

DEVELOPING A MODEL FOR PRINCIPALS' STEM LEADERSHIP CAPABILITY

To support principals' efforts to implement effective STEM education in their schools, we propose a model for principals' STEM capability. Our objective is to identify the necessary capabilities at a level of granularity sufficient to define trajectories for professional learning and develop programmes aimed at enhancing principals' STEM leadership. We have developed this framework by building on the research of others in the field of STEM education, including the lines of educational research associated with the constituent disciplines from the acronym—Science, Technology, Engineering and Mathematics.

Underpinnings of the framework

The synthesis of research in STEM education above indicated that any plausible model of STEM leadership must acknowledge the multidimensional nature of this role and accommodate the following characteristics: the centrality of STEM disciplinary and interdisciplinary knowledge (e.g., Holmlund et al., 2018); a focus on the solution of problems set in real-world contexts (e.g., Myers & Berkowicz, 2015; Wenner & Settlage, 2015); teachers' and students' dispositions and beliefs that promote ongoing engagement with STEM (e.g., Davis et al., 2019; Dong et al., 2020; Jeffries et al., 2019; Love et al., 2022); the use of tools that support investigatory approaches to teaching and learning (e.g., Dickes & Farris, 2019; Hoyles et al., 2010); and critical thinking capabilities needed to address complex open-ended situations (e.g., Gómez & Suárez, 2020; Goos et al., 2020; Li et al., 2019; Smetana & Coleman, 2015).

As our literature search did not identify any existing frameworks for leadership in integrated STEM education, we looked to identify models that included dimensions that aligned with the identified characteristics of STEM education—disciplinary and interdisciplinary knowledge; developing responses to real-world problems; dispositions and beliefs; the use of tools (particularly technological); and critical and creative thinking. We identified the Model of Numeracy for the 21st Century (Goos et al., 2014) as a construct based on dimensions that paralleled those required to encapsulate the capabilities required for effective STEM education. This model defined numeracy as an *across the curriculum endeavour* through four key dimensions—contexts, mathematical knowledge, tools and dispositions—which are

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activated through an analytical and evaluative meta-dimension, a *critical orientation*. The dimensions of the model are described in Table 1.

The Model of Numeracy for the 21st Century (Goos et al., 2014) was developed from a synthesis of literature on effective cross-curriculum numeracy teaching and learning practices. It has been validated and extended through research and development projects for over a decade, including programmes which have focused on: planning and teachers' numeracy teaching practice (Goos et al., 2014); the design of numeracy tasks (e.g., Geiger, 2018); initial teacher education instruction in numeracy (Forgasz et al., 2015; Goos et al., 2020); and support for critical orientation in the teaching of science (Geiger, 2019).

While four out of five of the dimensions of the Model of Numeracy for the 21st Century aligned with the characteristics of STEM education (real-world contexts, dispositions/beliefs, tools and critical orientation), the dimension of *mathematical knowledge* was too narrow for the intended purpose. This dimension was thus expanded to include the disciplinary and interdisciplinary knowledge associated with the constituent disciplines of STEM. It was this conceptualisation of the dimensions of STEM education that provided a framework for developing the set of capabilities required by principals to provide effective STEM education within their schools.

In the following section we elaborate on the identified dimensions of principals' STEM leadership capability based on a synthesis of literature in the field.

DIMENSIONS OF THE PRINCIPALS' STEM LEADERSHIP CAPABILITY MODEL

While all members of a school community have a role to play in the provision of high-quality education for young people, principals have the responsibility of leadership in all aspects of school life, including the development and maintenance of a positive STEM learning culture. The complexity of this role requires that principals' leadership capabilities be adaptable to the contexts in which they work. This includes the different leadership roles they assume when working with the range of stakeholders in their schools—teachers, students and the broader community. In the following subsections we describe our model in the form of a set of capabilities required to meet the demands of this role. These capabilities include both generic capacities related to broader leadership capabilities and capacities related specifically to coordinating the STEM endeavour within schools. A representation of the dimensions of this model is presented in Figure 1, as an extension of the Model for Numeracy in the 21st Century (Goos et al., 2014), and a summary of the characteristics of these dimensions, in the form of capabilities, is presented in Table 2. We elaborate on the nature of these capabilities individually.

TABLE 1 Description of the dimensions of the Model of Numeracy for the 21st Century (Goos et al., 2014).

Mathematical knowledge	Mathematical concepts and skills; problem-solving strategies; estimation capacities
Contexts	Capacity to use mathematical knowledge in a range of contexts, both within schools and beyond school settings
Dispositions	Confidence and willingness to use mathematical approaches to engage with life-related tasks; preparedness to make flexible and adaptive use of mathematical knowledge
Tools	Use of physical (models, measuring instruments), representational (symbol systems, graphs, maps, diagrams, drawings, tables, ready reckoners) and digital (computers, software, calculators, internet) tools to mediate and shape thinking
Critical orientation	Use of mathematical information to make decisions and judgements; add support to arguments; challenge an argument or position

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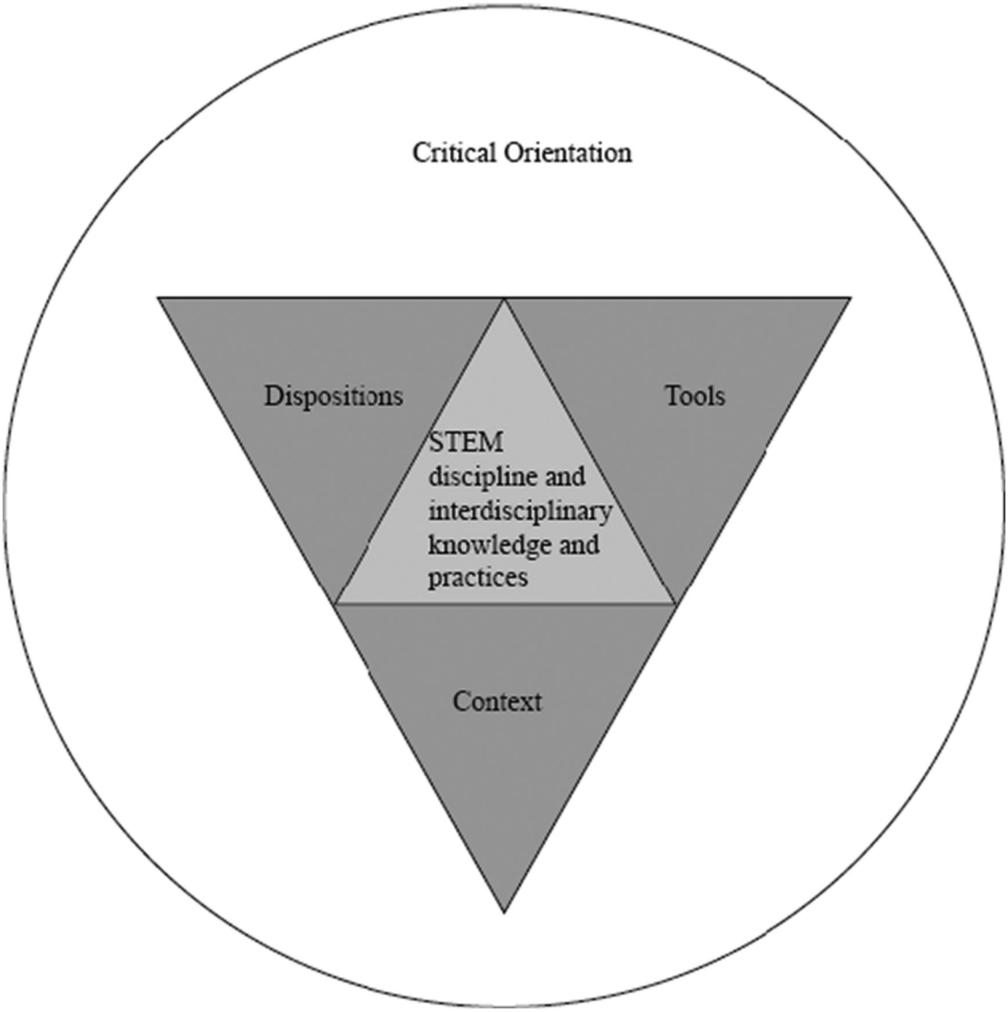

FIGURE 1 Dimensions of STEM capability.

STEM discipline-specific and integrated knowledge and practices

Central to our model are STEM discipline-specific and integrated knowledge and practices (Holmlund et al., 2018). STEM discipline knowledge involves concepts and practices related to Science, Technology, Engineering and Mathematics. STEM knowledge is typically brought to bear, as both discipline-specific and integrated knowledge, when seeking to address real-world problems (Bissaker, 2014; Myers & Berkowicz, 2015; Wenner & Settlage, 2015). While it would be an unreasonable expectation that principals possess a deep knowledge across all STEM disciplines, they must, in addition to their expertise in leadership of teaching and learning, have sufficient understanding to participate in meaningful discussions with relevant stakeholders—teachers, students, the school community and school partners. The individual elements of this dimension of STEM capability for principals (see Figure 1, and listed in Table 2) are elaborated upon further below.

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TABLE 2 Elements of STEM capability model—principals.

STEM discipline-specific and integrated knowledge and practices	• Awareness of concepts, skills and practices related to STEM disciplines • Awareness of the range of careers that require STEM skills and the role STEM plays in both individual wellbeing and national economic growth • Knowledge of relevant components of the Australian Curriculum and national policy documents • Capacity to lead initiatives aimed at promoting STEM teaching and learning (e.g., teacher professional learning groups, connections to industry) • Capacity to foster a STEM-positive school culture (positive student, teacher and parent attitudes towards STEM education)
Contexts	• Capacity to develop a vision for whole-school STEM teaching and learning relevant to specific educational environments • Capacity to promote STEM education to the broader school community and manage associated expectations • Strategic managing of the demands and opportunities associated with national and state curriculum and policy requirements and settings. This includes a reflection of Aboriginal and Torres Strait Islander perspectives in whole-school strategic planning (e.g., Australian Curriculum, Cross Curriculum Priority) • Capacity to establish partnerships (e.g., with industry, business, tertiary education) • Capacity to lead sustainable educational change specifically allied to the culture of the school
Dispositions	• Belief that all students and teachers can develop/enhance their STEM capability • Openness to the implementation of innovative STEM teaching practices • Confidence that innovative STEM programmes can be initiated, managed and brought to fruition • Flexible and adaptable change leadership practices so that all feel supported and encouraged in their engagement with the STEM project, regardless of differences in levels of knowledge, skill and confidence • Willingness to be personally and actively involved in establishing and sustaining the school STEM teaching and learning programmes • Flexible and adaptive thinking as their institution continues to innovate (e.g., openness to changes in school curriculum delivery structures and practices)
Tools	• Understanding of the role physical (e.g., models, measuring instruments), representational (e.g., symbol systems, graphs, maps, diagrams, drawings, tables) and digital (e.g., computers, robots, internet of things) tools play in STEM teaching and learning • Capacity to identify and procure resources that support effective STEM teaching and learning within their school context
Critical orientation	• Preparedness to make evidence-informed judgements and decisions about whole-school STEM teaching and learning programmes • Capacity to gather and analyse relevant data to inform future directions in promoting STEM teaching and learning • Extensive knowledge, skills and capacities related to leading complicated educational change effectively

Awareness of concepts, skills and practices related to STEM disciplines

To be effective in their role, principals must be aware of: the commonalities and differences between the constituent disciplines within STEM; how these different disciplines are related; and the strengths and limitations of applying STEM discipline knowledge and practices to real-world problems (Myers & Berkowicz, 2015; Wenner & Settlage, 2015). This awareness

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is necessary for the strategic planning for STEM teaching and learning in school settings and includes the development of curriculum and acquisition of relevant resources. Such planning is most effective when conceptualised and implemented in alignment with a coherent framework that locates STEM education within a school's broader educational goals (Baylor & Ritchie, 2002; Gerard et al., 2008).

Awareness of the range of careers that require STEM skills and the role STEM plays in both individual wellbeing and national economic growth

Under-enrolment in STEM courses at tertiary level, and STEM subjects in secondary education, are at odds with the increasing need for a STEM-capable citizenry and workforce (Hossain & Robinson, 2012; Wienk, 2017). This situation suggests that principals must be aware of employment opportunities and diverse pathways (e.g., further study, apprenticeships) to STEM careers (Bennison et al., 2018). In addition, principals must be capable of overseeing school processes that enable access to these opportunities, for example, the interpretation and dissemination of entrance requirements for further education in STEM to teachers and students (Maltese & Tai, 2011; Miller & Kimmel, 2012), including alternative pathways to tertiary education.

There is evidence that successful engagement with STEM subjects during schooling influences students' self-efficacy, aspirations and wellbeing (Wang & Degol, 2013). Other research indicates that students from diverse backgrounds can be engaged in schooling by incorporating learning experiences relevant to their culture (Calabrese Barton & Tan, 2018). The powerful economic incentive offered by STEM careers can also be attractive to students from lower socioeconomic and disadvantaged backgrounds (Calabrese Barton & Tan, 2018; Engberg & Wolniak, 2013). Principals need to be aware of each of these influences and opportunities to enhance student engagement and success in STEM education.

Knowledge of relevant components of the Australian curriculum and national policy documents

Responsibility for the design of STEM education programmes in schools demands that principals are abreast of change related to curriculum and assessment requirements, as well as other local or national policy settings. In Australia, for example, the government has prioritised a national strategy for STEM education with renewed focus on mathematics and science curricula, as well as initial teacher education in the STEM disciplines (Prinsley & Johnston, 2015). Similarly, in the United States, both national and local initiatives have been implemented to increase student engagement with STEM education, in the wake of the National Research Council's review of national competitiveness in science and technology (National Research Council, 2007; Salzman & Benderly, 2019). Specific strategies have been developed in the United Kingdom to improve the capability of STEM educators, increase STEM enrolments and enhance levels of student achievement in STEM (Department for Business Innovation and Skills, 2014; HM Treasury, 2004). In each of these initiatives, principals were considered key to the implementation of STEM education strategies in schools. Principal capability is required to translate broader policy settings, strategic plans and the demands of curriculum into school-based initiatives that accommodate the specific contextual features of their school communities (e.g., Bissaker, 2014; Marshall, 2009; Shulman, 2002).

Capacity to lead initiatives aimed at promoting STEM teaching and learning

The development of engaging and relevant STEM learning experiences requires the capacity to foster a collaborative approach to curriculum design with, and among, teachers (Avendano et al., 2019; Goos, 2006; Myers & Berkowicz, 2015; Smetana et al., 2016). In this role, principals provide support, guidance and facilitate ongoing STEM-related professional learning (Goos, 2006; Hung & Mui, 2009). According to Baylor and Ritchie (2002) and Gerard et al. (2008), this requires principals to take an active role in the planning and implementation of STEM initiatives, as this signals its importance to the school community.

There is also an important role for principals to play in the development and maintenance of strategic partnerships with stakeholders or partners. These might include businesses and agencies (private, community, government), healthcare organisations and tertiary institutions that can contribute to school STEM education programmes by providing students with examples of Science, Technology, Engineering and Mathematics applications. Such initiatives can also broaden students' exposure to post-school career pathways (Myers & Berkowicz, 2015).

Capacity to foster a STEM-positive school culture

Central to principals' STEM leadership is their capacity to foster a STEM-positive school culture. Such a culture is key to the success of STEM education programmes because effective changes to curriculum and pedagogy are dependent on their alignment with the existing school culture or its planned evolution (Agbo, 2015). Principals build positive school cultures through active involvement in initiatives directed at change, engagement with school learning communities and involvement in staff decision-making processes (Halverson et al., 2011). Principals' communication must involve all stakeholders and be delivered in a way that is meaningful to each group (Fullan, 2002).

The ‘buy in’ of community members into a school's culture is key for effective implementation of initiatives in STEM education. Fostering positive student, parent and community attitudes towards STEM requires the development of a positive school STEM culture (Han, 2017). Principals, therefore, must make STEM education, that encourages contributions from the wider school community, an ongoing school priority (Baylor & Ritchie, 2002; Gerard et al., 2008).

Contexts

Finding solutions to problems within real-world contexts is central to STEM education. The notion of context is also essential to understanding the capabilities required for effective leadership in STEM education as principals must adapt their leadership of STEM to the circumstances of their school and its community. The individual elements of this dimension of STEM capability for principals (Figure 1, Table 2) are elaborated upon below.

Capacity to develop a vision for whole-school STEM teaching and learning relevant to specific educational environments

The sustainability of school STEM education initiatives is dependent on the development and communication of a shared school vision with which policy, staff recruitment, curriculum,

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assessment and approaches to teaching and learning align (Darling-Hammond et al., 2007). An effective vision for STEM teaching and learning does not exist in isolation, as it must be operationalised as a whole-school approach that is inclusive of all stakeholders, accommodates national and state policy directives and takes account of the unique characteristics of a school (Bolman & Deal, 2017; Neumerski, 2013). This includes building the capacity of all members of staff in order to bring about changes in classrooms (Hung & Mui, 2009). To do so, principals must cultivate trusting relationships with all stakeholders, and provide clear and consistent messaging about the school's goals, values and vision (Smetana et al., 2016).

Capacity to promote STEM education to the broader school community and manage associated expectations

In their promotion of STEM education, principals must consider and communicate how different groups of students will be supported to succeed. This includes attention to issues of diversity and equity related to, for example, girls, indigenous people, minority communities, children with disabilities and children at the edges of academic achievement (Osborne et al., 2019; Suad Nasir & Vakil, 2017). Although special programmes have provided support for students identified as 'talented', they have also been seen as exclusive, thus sending the message that STEM education is for the very able rather than for all (Seed, 2018).

Strategic managing of the demands and opportunities associated with national and state curriculum and policy requirements and settings

The strategic management of the national and state curriculum and policy requirements is a core component of principals' work. It is essential, therefore, that principals understand the 'big ideas' in STEM and how these are embedded and articulated in curricula, policy requirements and directives (AITSL, 2014; Steinberg & Diekman, 2017). At the same time, principals must balance the mandated requirements of curriculum and other policy directives with the time teachers need to develop engaging opportunities for student learning in STEM (Hung & Mui, 2009).

Capacity to establish partnerships

The success of STEM initiatives in schools can be enhanced by principals' ability to establish and maintain partnerships with stakeholders, for example, industry and business, further and higher education (Johnson, 2013). Working with school partners provides opportunities to enrich students' learning experiences while exposing them to potential career options (Nebres, 2009).

Capacity to lead sustainable educational change specifically allied to the culture of the school

In addition to fostering a STEM-positive school culture, principals must have the capacity to lead change in a way that aligns with a school's unique culture (Agbo, 2015; Smetana & Coleman, 2015). This means principals must ensure that educational changes are implemented in a way that supports teachers and students, while at the same time accounting for the specific nuances of their school environment (Lamb, 2010; Smetana & Coleman, 2015).

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Dispositions

It has been established that positive *dispositions* towards taking intellectual risks by thinking differently and flexibly is key to effective problem-solving in many disciplines (e.g., Boaler & Greeno, 2000; Davis et al., 2019; Gresalfi & Cobb, 2006). The individual elements of this dimension of STEM capability for principals (Figure 1, Table 2) are outlined below.

Belief that all students and teachers can develop/enhance their STEM capability

Principals' beliefs about their school communities' capacity to enhance their STEM capability is an important prerequisite for bringing about positive STEM cultures in their schools (Beswick & Jones, 2011). This indicates that principals must be able to inspire their school community to take on challenges associated with change. Such inspiration necessarily rests upon a belief that all students, teachers and members of the school community can develop/enhance their STEM capability (Dempsey, 2007; Dong et al., 2020; Shen et al., 2010) and is vital because individuals, and particularly teachers, can feel vulnerable as they undertake professional learning (York-Barr & Duke, 2004). The development of a positive STEM culture within schools is needed to counter the negative attitudes students sometimes encounter when engaging with peers and other members of the school community (Jeffries et al., 2019; Lee, 2015; Lichtenberger & George-Jackson, 2013).

Openness to the implementation of innovative STEM teaching practices

Principals are responsible for establishing a school culture that is either conducive or inhibitory to change (Rogers, 2007). Sourcing and allocating STEM resources, structuring of STEM programmes and staffing are all drivers of change for which school leadership is responsible. Principals' openness to the adoption of innovative teaching practices and the associated allocation of resources has a direct impact on the operationalisation of new directions for STEM, such as increased student learning opportunities (Praisner, 2003; Rogers, 2007).

Confidence that innovative STEM programmes can be initiated, managed and brought to fruition

Principal self-efficacy is integral to lasting school-wide change, including the confidence to initiate and manage the implementation of innovative STEM programmes (Beswick & Jones, 2011). Principals must remain confident when their school faces challenges, such as staff resistance to change, disengagement or low motivation, budgetary constraints, technical difficulties, challenges with maintaining resources and external pressures to implement change (Toprakci, 2006). Although there is limited research into how principals develop the confidence needed to foster school STEM education programmes, Stohlmann et al. (2012) have provided evidence that STEM-specific leadership training can enhance the confidence and positive attitudes needed to initiate and maintain STEM education innovation.

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Flexible and adaptable change leadership practices so that all feel supported and encouraged in their engagement with the STEM project, regardless of differences in levels of knowledge, skill and confidence

As well as having confidence in their ability to initiate and manage change, principals need to be capable of adopting flexible leadership practices that ensure all feel supported and encouraged in their engagement with STEM (Buckner & Boyd, 2015; Ohlson et al., 2016).

Willingness to be personally and actively involved in establishing and sustaining the school STEM teaching and learning programmes

Kaptzon and Yemini (2018) argued that effective school change is more likely when principals take a prominent role in the management of school STEM programmes. This finding is consistent with that of Smetana et al. (2016), that science teachers become more autonomous in their work when principals take an active role in decisions about curriculum and pedagogy because this instils a sense of value and trust in their work. Similar findings have been reported in research related to both numeracy and technology education (Baylor & Ritchie, 2002; Gaffney, 2012), where the active involvement of school leaders in subject-based decision-making enhances their credibility as leaders of change. This sense of trust and value is also important to the long-term sustainability and ongoing success of STEM education programmes (Bissaker, 2014; Hung & Mui, 2009).

Flexible and adaptive thinking as their institution continues to innovate

Principals need to be flexible and adaptive in their approach to leadership as STEM teaching and learning evolves in their schools. Key to STEM education are the notions of change and innovation in, for example, curriculum delivery structures and practices, which will require continuous adaptation over time. This means that for a STEM programme to retain currency, it must be subject to continuous review and revision that is informed by examples of successful implementation (Nadelson & Seifert, 2017).

Tools

The role of tools, as mediators of meaning-making, has been central to the practice of each of the constituent disciplines of STEM (e.g., Artigue, 2002; Drijvers & Weigand, 2010; Gerard et al., 2008; Pea, 2004). Tools can be physical (e.g., rulers, beakers, litmus test paper), representational (e.g., maps, circuit diagrams) or digital (e.g., calculators, computers, digital scales) (Geiger et al., 2015). Such tools are ubiquitous within civic and personal life (e.g., Dickes & Farris, 2019; Noss et al., 2000; Zevenbergen, 2004). The individual elements of this dimension of STEM capability for principals (Figure 1, Table 2) are elaborated upon below.

Understanding of the role physical, representational and digital tools play in STEM teaching and learning

Digital tools are now essential in all STEM subjects, for example, searching databases of statistical information in mathematics, conducting experiments in science, enacting the

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design elements of engineering and in all aspects of technology studies. Hoyles et al. (2010) argued that digital tools underpin the techno-mathematical literacies essential to functioning effectively in the workplace. For principals to make effective decisions about curriculum and pedagogy, they must understand the role that tools, and especially digital tools, play in STEM teaching and learning.

Capacity to identify and procure resources that support effective STEM teaching and learning within their school context

The implementation of a school's vision for STEM education requires decisions about resources, staff support and staff professional learning programmes (Gerard et al., 2008). These decisions include the allocation of resources that support STEM teaching and learning. Such resources include both personnel (e.g., leaders, teachers, support staff) and the support required to embed new tools into their instruction, for example, professional learning programmes and/or changes to timetabling to access facilities (Burke, 2005; Hung & Mui, 2009). Principals must also consider potential changes to their school's physical environment when specialised, physical spaces such as science laboratories are needed for the use of STEM tools (O'Grady, 2009).

Critical orientation

Adopting a critical orientation to problems involves weighing up evidence to form judgements or make decisions (Gómez & Suárez, 2020; Goos et al., 2020). For principals, this relates to strategic planning in relation to curriculum design, staff recruitment, teacher professional learning opportunities and the acquisition and deployment of school resources. The individual elements of this dimension of STEM capability for principals (Figure 1, Table 2) are described below.

Preparedness to make evidence-informed judgements and decisions about whole-school STEM teaching and learning programmes

Principals' capacity to make evidence-based decisions about STEM teaching and learning programmes is dependent on their ability to identify, understand, analyse and utilise relevant data. This capacity is reliant on the data that can be accessed, gathered and analysed to determine the strengths and weaknesses of current programmes in order to target improvement (Dempsey, 2007; Shen et al., 2010). Examples of this data include national assessment results and in-school diagnostics.

Evidence-informed decision-making, particularly regarding allocation of resources and hiring practices, is also reliant on a principal's understanding of STEM subjects (Politis et al., 2007; Rayfield & Wilson, 2009) and curriculum and assessment pressures (Hung & Mui, 2009). Such decisions demonstrate the value they place on both STEM learning (Hung & Mui, 2009; Li et al., 2019) and the quality and direction of teacher work (Rayfield & Wilson, 2009). A careful, evidence-based approach to strategic planning builds motivation among teachers and the school community (Abdullahi & Jimoh, 2018) and ensures the sustainability of future endeavours (Goos, 2006).

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Capacity to gather and analyse relevant data to inform future directions in promoting STEM teaching and learning

A crucial element of evidence-informed decision-making is the capacity to identify, locate, interpret and evaluate information. For principals, this means they must know how to collect data related to the quality and effectiveness of their STEM programmes, analyse the data and draw credible conclusions from the analysis. Dempsey (2007) and Shen et al. (2010), for example, stressed the importance of the effective use of school test data to improve school planning and student learning outcomes. Principals must also instigate professional learning programmes aimed at enhancing the data literacy of teachers and other school stakeholders, in order that they understand the evidence behind reasons for change (Mandinach & Gummer, 2016).

Extensive knowledge, skills and capacities related to leading complicated educational change

To be effective STEM leaders, principals must possess a combination of leadership, business management and STEM-specific instructional leadership capabilities (Blanton & Harmon, 2005; Gaffney, 2012). The need to appropriate this range of capabilities highlights the complexity of the challenges associated with building a positive STEM school culture (Hung & Mui, 2009; Smetana & Coleman, 2015). To exemplify, Toprakci (2006) highlighted that in order for principals to effectively lead the integration of changes in the ICT curriculum, they must possess the knowledge and skills to manage budgetary limitations, technical knowledge and the wherewithal to direct staff interest, motivation and adaptability to change. Managing these complex demands requires critical capabilities, including evidence-based decision-making (Steinberg & Diekman, 2017) and flexible and adaptable leadership when making decisions about directions for teacher capacity-building in order to foster sustainable improvements to STEM education (Branson et al., 2018).

DISCUSSION AND CONCLUSION

In this paper we have addressed the research question: *What capabilities are required by principals to undertake effective STEM leadership in their schools?* by developing a model for principals' STEM leadership, which is based on the capabilities that principals require to be effective leaders of STEM education in their schools. The model is defined by five dimensions of principals' STEM capability: (1) STEM discipline-specific and integrated knowledge and practices; (2) contexts; (3) dispositions; (4) tools; and (5) critical orientation. These dimensions represent distinct, but interrelated, capacities that principals require for effective leadership of STEM in their school communities. We have provided elaborations, in the form of capabilities, of these dimensions which are supported by synthesis of relevant research literature. These capabilities provide detail that has implications for both theory and practice.

Evidence of increasing research interest in STEM education can be seen in the emergence of a number of new journals in this field, for example, the *International Journal of STEM Education*, the *Journal for STEM Education Research* and *Research in Integrated STEM Education*. Research literature to date, however, has tended to focus on teaching and learning within integrated STEM programmes, or in relation to the constituent disciplines (English, 2016). There appears to be little by way of research into the role of leadership in STEM education within schools, including that of principals and middle leaders

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(e.g., De Nobile, 2018; Jorgensen, 2016). This gap has implications for the rollout of STEM programmes in schools. The model for principals' STEM leadership presented in this paper is therefore a contribution to new knowledge in the field. The dimensions that frame the capabilities are also original contributions to research into the leadership of STEM education, as no previous studies have attempted to articulate and categorise the capabilities required of principals to effectively lead STEM in their schools.

The model for principals' STEM leadership has a range of implications for practice, including as a framework for: strategic planning in relation to initiating, implementing and sustaining STEM education programmes; the professional learning of principals and middle leaders in relation to supportive and effective STEM leadership; the promotion of a positive STEM learning culture across school communities; and the commissioning of teachers' STEM professional learning.

We see four major directions for future research in STEM education leadership. First, the empirical substantiation of the dimensions and capabilities that define the model for principals' STEM leadership. Second, testing the effectiveness of the model for guiding school planning, professional learning for school leaders and the development and maintenance of positive STEM learning cultures. Third, there is opportunity to generate parallel STEM capability sets for teachers, students and the school community more broadly. Finally, the development of the capability set required by STEM middle leaders, consistent with calls in the literature for ways to support the role of middle leaders in guiding STEM teaching and learning (Lipscombe et al., 2020).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

ETHICS STATEMENT

Ethical approval for this study was granted by the University of Tasmania, Australia. It complied with the Australian Privacy Principles.

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