Teaching and Teacher Education 141 (2024) 104490

Contents lists available at ScienceDirect

Teaching and Teacher Education

journal homepage: www.elsevier.com/locate/tate

Research paper

Teacher learning community for AR-integrated STEM education

Xiao-Fan Lin [a,b,*], Thomas K.F. Chiu [c], Shucheng Luo [d], Seng Yue Wong [e], Huijuan Hwang [d], Sirui Hwang [d], Wenyi Li [d], Zhong-Mei Liang [f], Shiqing Peng [a], Wenkai Lin [g,**]

[a] School of Education Information Technology, Guangdong Engineering Technology Research Center of Smart Learning, Guangdong Provincial Institute of Elementary Education and Information Technology, South China Normal University, 510631, Guangzhou, China
[b] Guangdong Provincial Philosophy and Social Sciences Key Laboratory of Artificial Intelligence and Smart Education, Institute for Artificial Intelligence Education, South China Normal University, 510631, Guangzhou, China
[c] Department of Curriculum and Instruction & Centre for Learning Sciences and Technologies & Centre for University and School Partnership, The Chinese University of Hong Kong, Hong Kong
[d] School of Education Information Technology, South China Normal University, 510631, Guangzhou, China
[e] Centre for Internship Training and Academic enrichment (CITrA), University of Malaya, Kuala Lumpur, Malaysia
[f] Zhixin South Road Primary School, 510000, Guangzhou, China
[g] College of Teacher Education, South China Normal University, Teacher Education College of Guangdong-Hong Kong-Macao Greater Bay Area, 510631 Guangzhou, China

A R T I C L E I N F O

Keywords:
STEM teaching
Teacher learning community
Augmented reality
Perceived support

A B S T R A C T

This study used a social network analysis and a content analysis to identify 52 teachers' perceptions to investigate the mechanisms of teachers' roles and teachers' perceived support from a learning community to overcome barriers to AR-integrated STEM teaching. The findings revealed that when teachers occupy more powerful and central roles in the AR-integrated STEM teaching community, they may perceive higher-order support for overcoming the corresponding barriers to AR-integrated STEM teaching. Furthermore, this study developed a framework for promoting teachers' professional development in AR-integrated STEM teaching by clarifying the hidden role and actual support, which was rarely emphasized in past studies.

1. Introduction

Augmented Reality (AR) is an emerging technology that uses intelligent technology to enhance or expand the scene of the real world by the additional information generated by the virtual system (Chalasani et al., 2018; Lin et al., 2023). The utilization of AR in integrating Science, Technology, Engineering, and Mathematics (STEM) education is seen as an innovation that could advance our existing educational practices and policies. For example, the use of the AR environment in the community could enhance the realism of the teaching-learning processes (Rodríguez-Abad et al., 2021), develop the features for positive experience (Baabdullah et al., 2022), and support teachers to share knowledge for communicating teaching issues in the community (AlNajdi, 2022). This innovation is challenging for teachers; therefore, teacher learning is crucial to its success. The barriers to AR-integrated STEM teaching were teacher anxiety, digital literacy, STEM disciplinary knowledge, and pedagogies for project-based learning (Chai et al., 2020; Sırakaya & Alsancak Sırakaya, 2022; Urválková & Surynková, 2021). A teacher learning community that provides substantial support to teachers can address the challenges (Takeuchi et al., 2020) and promote the use of AR to support STEM teaching. Therefore, it is crucial to offer teachers substantial support for effective AR-integrated STEM teaching.

In a STEM teacher learning community, teachers with different subject backgrounds and digital literacy skills can interact with each other and grow together (Barragán-Sánchez et al., 2020). The

* Corresponding author. School of Education Information Technology, Guangdong Engineering Technology Research Center of Smart Learning, Guangdong Provincial Institute of Elementary Education and Information Technology, South China Normal University, 510631, Guangzhou, China.
** Corresponding author. College of Teacher Education, South China Normal University, Teacher Education College of Guangdong-Hong Kong-Macao Greater Bay Area, 510631, Guangzhou, China.
E-mail addresses: linxiaofan@m.scnu.edu.cn (X.-F. Lin), tchiu@cuhk.edu.hk (T.K.F. Chiu), 919118249@qq.com (S. Luo), wongsengyue@um.edu.my (S.Y. Wong), 3347775091@qq.com (H. Hwang), 793522756@qq.com (S. Hwang), liwenyi@pku.edu.cn (W. Li), 351632147@qq.com (Z.-M. Liang), 2475317832@qq.com (S. Peng), 14377866@qq.com (W. Lin).

https://doi.org/10.1016/j.tate.2024.104490
Received 5 April 2023; Received in revised form 26 December 2023; Accepted 18 January 2024

community moves them from novices to advanced practitioners. They can seek help by asking community members and sharing their ideas and experiences with other members. For example, they could discuss how to set a real-life problem for interdisciplinary STEM teaching, or share experiences of how to integrate emerging technologies in STEM teaching (Kopcha, 2012; Shiau et al., 2018). In general, the community could foster STEM teacher's growth in two areas: technology integration and integrated STEM education (Glazer & Song, 2005; Kopcha, 2012), which indicates the potential of a teacher learning community to facilitate AR-integrated STEM teaching for teachers.

Studies on teacher learning communities suggest that teachers' roles and perceived support would affect how STEM teachers grow. The importance of teachers' perceived support in a community has been noted for solving teachers' barriers to using technology in multidisciplinary education (Li & Choi, 2013). However, teachers with different roles may perceive support from community members differently. For example, pre-service teachers were found to perceive more support than in-service teachers in teacher professional communities (López Solé et al., 2018). In other words, teachers' roles may be associated with their perceived support from members (Baker-Doyle & Yoon, 2011) and perceived outcomes (e.g., individual and group achievements) (Al-Balushi & Al-Abdali, 2015; Lin et al., 2016; Woodland et al., 2021). To the best of our knowledge, studies on teacher education in AR-integrated STEM education have focused on teachers' attitudes, knowledge (Wahono & Chang, 2019), perceptions, and STEM competencies (Nguyen et al., 2020). Hence, there is a serious lack of relevant studies on the relationships between teachers' roles and perceived support in teacher learning communities for AR-integrated STEM teaching. Accordingly, this study aimed to fill this gap by investigating the relationships between teachers' roles and perceived support in a teacher learning community for AR-integrated STEM teaching.

2. Literature review

2.1. Teacher learning community for AR-integrated STEM teaching and teacher roles

In this study, AR-integrated STEM teaching refers to using AR to support STEM teaching that focuses on interdisciplinary learning (Ibáez & Delgado-Kloos, 2018). Its learning outcomes include knowledge and higher-order thinking. This teaching allows students to visualize complex concepts in a way that is impossible to represent in the real world (Altmeyer et al., 2020). This visualization fosters students' cognitive processes during learning. For example, Lo et al. (2021) created an AR application to foster school students' better understanding of environmental education. Although AR could better engage students in integrated STEM learning, it is challenging for an individual teacher to design effective instruction. To design effective instruction, teachers need to take the four STEM disciplines' perspectives into account and understand the affordances of AR (Margot & Kettler, 2019). Most teachers are familiar with one or two disciplines; some may be unfamiliar with AR technology; others may have more interdisciplinary teaching experience. They need to work with teachers with different academic backgrounds and experience in teaching with technology. Therefore, this reflects that teacher learning communities are necessary to help teachers gain ideas from different disciplinary approaches and teaching views (Margot & Kettler, 2019).

A teacher in a teacher learning community for multi/interdisciplinary education has different roles since the members have their own expertise/teaching subject domains. Teachers who share resources and knowledge in the existing and trusted community are referred to as bridges that connect different networks of people. They are willing to interact with other members. Among the different roles in the trusted community, some teachers may serve as guides and mentors who promote integrated teaching in multi/inter-disciplinary education. Interactions/communications between the teachers with different roles in the community will foster their growth. Such a learning community forms a social network where people spread information, channel personal or media influence, and are allowed to change their attitudes or behaviours. The community can be viewed as the collaborative culture of a school, which is characterized by sharing common values, visions, and learning orientations (Toikka & Tarnanen, 2022).

In this study, the teacher learning community refers to the interdisciplinary and intercultural AR-STEM teaching community collaborating with teachers of different subjects to focus on the same goal of addressing teaching difficulties and challenges in STEM education for their professional development. Understanding the network characteristics can provide significant and meaningful information about teacher learning for AR-integrated STEM teaching (Ma et al., 2016).

The multi-interdisciplinary teachers serve different roles based on network characteristics. These roles may reflect members with different degrees of how central they are in the community. These roles also indicate the strength of collaboration among teachers. Literature suggests that teachers' roles in the community can be determined from two perspectives: participatory and knowledge-building. (1) Participatory perspective: participant roles include readers, contributor, collaborator, and leaders (Preece & Shneiderman, 2009; Strijbos & Laat, 2010; Wenger et al., 2002). (2) Knowledge-building perspective: participants roles include facilitator, collector, and expert (Rozewski et al., 2015; Ma et al., 2016). Both perspectives provide a conceptualization of the different roles of teachers in the learning community. The participatory perspective is relating to describing the engagement and interaction between teachers, whereas the knowledge-building perspective has associated with describing the interaction between teachers' roles and knowledge. Thus, teachers tend to play different roles in the teacher learning communities (Anspal et al., 2019; Polizzi et al., 2018; Zhang et al., 2022).

Teachers' roles refer to how teachers from multiple disciplines in different roles may offer or obtain different perceived support in collaborative teacher professional development. They could be measured regarding the degree of centrality (DC) and structural holes (SH), and their functions could vary across communities (e.g., trusted network, different network) (Polizzi et al., 2019; Yondler & Blau, 2023). DC refers to the degree of teachers' centrality in the network, while SH is defined as a broker between contacts in the network where teachers on either side of the SH have access to shared knowledge and resources (Demir, 2021). On the one hand, by analyzing the structural holes, it is feasible to identify a type of teacher who is considered a broker within or between communities. Zhang et al. (2022) showed that since sharing resources and knowledge is essential to support the development of teacher communities, teachers with sufficient resources and the ability to share resources are expected to perform the role of a broker or channel between communities. On the other hand, the degree of centrality demonstrates the teachers' intensity of interaction within or between communities. Anspal et al. (2019) suggested that it is critical for a teacher learning community to have strong interactions, shared goals, and central leadership. The leadership of a highly central role provides not only spiritual support to the community but also ensures a close interaction and shared goal based on exchanging ideas between teachers in the learning community.

Second, in terms of helping teachers reduce the barriers to AR technological integration, the teacher learning community may be a solution that facilitates teachers' learning of technology-integrated teaching to promote their outcomes (Kopcha, 2012). There is more efficient information sharing among the teachers in STEM-teaching-focused communities of practice than in non-adopting communities of practice (Ma et al., 2016). Participation in a community provides teachers with the opportunity to work together to develop shared meanings with activities such as questioning, clarifying, and negotiating (Karam et al., 2018). In the process, teachers regularly share solutions to their problems and receive support while integrating technology (Glazer & Song, 2005; Hughes & Ooms, 2004). There is also evidence showing that the main benefit of participation in the interdisciplinary community is helping teachers acquire sufficient knowledge related to instructional design (Chai et al., 2020). Moreover, collaborative inquiry and interaction in a community of practice may also benefit teachers by providing opportunities for reflection (Butler et al., 2004). Teachers' learning in a community effectively supports professional development (Kelley et al., 2020; Vossen et al., 2020). They benefit greatly from learning within a STEM teaching community (Kelley et al., 2020). Assessing teachers' perceptions plays a critical role in preparing for such effective professional development (Khuyen et al., 2020). The above studies implied that teachers' roles in the learning community would influence their growth and professional development (Kelley et al., 2020; Vossen et al., 2020). Accordingly, a thorough investigation of teachers' views of support for overcoming the barriers to AR-integrated STEM teaching is needed since such barriers are a significant issue in integrating appropriate pedagogical strategies with AR for enhanced STEM teaching results.

2.2. Perceived support

The term "barrier" has been viewed as a difficulty in understanding complex concepts or a lack of a high degree of content knowledge of multidisciplinary subjects (Baker-Doyle & Yoon, 2011; Chai et al., 2020). Research has indicated the importance of teachers' perceived support from each other when they encounter barriers regarding technology-integrated instruction (Lin et al., 2020). For example, a previous study was devoted to reducing extrinsic barriers by improving resources (e.g., equipment) (Glogger-Frey et al., 2015). If a budget is sufficient, the barriers to resources can be eliminated (Donnelly et al., 2011). In addition to solving extrinsic barriers (e.g., technical problems), the support to face intrinsic barriers is perceived as social capital (i.e., the wide range of resources in the teaching community, such as knowledge, ideas, instructional resources, etc), which reduces teachers' barriers at lower levels. Researchers have worked to improve teachers' teaching abilities, collaborate, and support teachers' changing beliefs to reduce intrinsic barriers, such as teachers' beliefs about technology. For example, Yoon et al. (2020) found that reducing higher-order barriers, e.g., classroom management in technology supported instruction, requires more complex and indirect support from social capital. Chiu et al. (2021) provided good references for probing teachers' professional development by proposing a framework for pedagogical design thinking, involving gaining knowledge of design thinking, nurturing a design thinking mindset, and emphasizing teachers' needs for support. Chen et al. (2022) used hierarchical system to develop a theoretical framework of teachers' perceived barriers that range from lower-order barriers (e.g., extrinsic barriers and second-order intrinsic barriers) to higher-order barriers (e.g., third-order barriers to classroom management and fourth-order barriers regarding a lack of design thinking).

Despite the theoretical framework that has been developed, little attention has been paid to teachers' roles and their relations to perceived support for overcoming these barriers. Teachers who are provided with suitable professional training and support are more likely overcome barriers and improve instructions (Hammack & Ivey, 2019). It is important to recognize the links between how to set the roles and how leaders support others in a community. However, this seems to be no general definition of teachers' perceived support for overcoming barriers to AR-integrated STEM teaching in the literature. Thus, there is a need to identify participatory approaches to measure the hierarchical system of different types of teachers' perceived support. Research is needed to clarify teachers' perceived support in this specific context.

2.3. Relationship between teacher roles and perceived support

Literature has revealed that positive teachers' roles in a learning community are related to the teachers' support. First, more core teachers' roles in a learning community could contribute to the trust related to the improvement of teaching abilities, sharing related essential information for effective teaching, and the distribution of more specific resources for teachers or peer support (Lin et al., 2016; Neal et al., 2011; Penuel et al., 2009). The increased support is predictive of overcoming barriers that might hinder effective instructional practices (Judson & Lawson, 2007). Second, studies showed that the more complex and active memberships of the teachers in STEM-teaching-focused communities of practice, the more abundant and more efficient the information sharing among those teachers (Ma et al., 2016). However, if an individual plays a marginal role in the community, they will not be able to access the group's social capital (Mehra et al., 2001). A member's role significantly contributes to their social capital (Baker-Doyle & Yoon, 2011). The social capital available to teachers can predict their perceived support for overcoming barriers. Therefore, investigating the relationship between teachers' roles and perceived support will give a better theoretical understanding of participatory approaches to overcoming barriers to AR-integrated STEM teaching.

Overall, despite previous studies mentioning the importance of teachers' roles in AR-integrated STEM teaching communities (Ibáez & Delgado-Kloos, 2018; Sırakaya & Alsancak Sırakaya, 2022), these studies did not clarify in detail how their roles may benefit their AR-integrated STEM teaching. Some of their studies have discussed that teachers' roles would affect the accumulation of the social support teachers gain. Therefore, this study hypothesized that teachers' roles from the learning community can significantly predict their perceived support for overcoming barriers to AR-integrated STEM teaching.

2.4. Theoretical background

This study applied graph theory as the theoretical framework to explore the relationship between teachers' roles in the STEM teacher learning community. Graph theory has been demonstrated to be a valuable tool for modelling real-world issues. It was first applied in the field of mathematics to understand how different parameters and graph structures are connected to each other (Zweig & Zweig, 2016). Since then, graph theory has gradually been further applied in education, and makes it possible to obtain a visualization picture of relationships illustrating how different roles of people communicate and interact with others in the community (Chai et al., 2019). For example, graph theory has been employed to identify the roles of referential members in a learning community (e.g., Leader and Periphery actor) and to visualize the contribution they make within the process of learning exchange (Peeters & Pretorius, 2020). Moreover, Social network analysis (SNA) and graph theory have similarities and differences. SNA aims to study network structure and it is built on graph theory's social and mathematical principles. It is a particular application of graph theory that more focuses on relating the graph's characteristics to understand information flow, social capital, as well as the development of beliefs and identities, within a group of people (Chai et al., 2019). This analysis describes networked structures in terms of nodes (individual actors, individuals, or objects inside the network) and ties, edges, or connections (relationships or interactions) that connect them. Structures are often visualized through graphs in that nodes are represented as points, and ties are represented as lines. The visualizations offer a method for evaluating structure by altering the visual representation of their nodes and edges to reflect qualities of interest. This study used graph theory and SNA to analyze the AR-integrated STEM teaching community's interpersonal structure and group interactions to explain how teachers in a professional learning community share their knowledge and resources, collaborate, and interact with each other.

Teachers in the community for STEM interdisciplinary teaching have different teaching background that can be seen as culture in differents cultural contexts. Sociocultural learning theory is another theory that can explain interaction in the teacher learning community. This theory emphasizes that learning takes place through social interactions and communications with members with different backgrounds, such as peers, leaders, mentors, mentees, and experts (Vygotsky, 1986). Learning depends on the interaction with others via the learning activities in the digital or/and face-to-face communication channels. The relationship between teachers' roles and their perceived support could be explained by the theory.

2.5. Significance of this study

Previous studies have focused on teachers' surface roles (i.e., teachers' occupational roles), but have failed to uncover the needed support for their roles. It may be difficult for teachers to conduct AR-integrated STEM teaching due to the resistance to AR use (Sırakaya & Alsancak Sırakaya, 2022), and the distractions and cognitive loads caused by AR. In addition, the previous studies do not show the relationships between teachers' roles and perceived support from the perspective of interactive content. Moreover, most studies on STEM teacher professional learning have explored teachers' attitudes and knowledge in STEM education (Wahono & Chang, 2019) and teachers' perceptions of STEM education, STEM competencies, and difficulties in implementation STEM teaching (Nguyen et al., 2020). Therefore, it is necessary to use SNA to uncover teachers' actual and urgent support in the learning community.

2.6. Research goal and questions

The main goal of this study was to investigate the relationships between teachers' roles and perceived support in a teacher learning community for AR-integrated STEM instruction.

The three research questions are listed as below.

RQ1. What are teachers' roles in a teacher learning community for AR-integrated STEM instruction?

RQ2. What support do teachers perceive in the community?

RQ3. What are the relationships between the teachers' roles and perceived support?

3. Method

3.1. Research participants and context

The Ministry of Education has introduced a series of policies to support interdisciplinary education since 2018. In this context, the community and participant selection process would be based on the following criteria in this study: (a) The instruction within the community would be primarily teaching on the topic of AR-integrated STEM; (b) Community members need to have an intention to practice or experience on AR-integrated STEM teaching; (c) Community members need to be willing to interact and collaborate with other teachers. To ensure the quality of the studies, the participants who met the criteria above were selected for the study. The rest of the teachers will be excluded (e.g., teachers with low engagement and activity). As a result, a Guangdong-Hong Kong-Macao Greater Bay Area community which was relatively well-developed is randomly selected for current study. This study involves 52 teachers as participants. These teachers were from different schools engaged in online and offline collaboration on an AR-integrated STEM teaching system. They were able to engage in online discussion boards, where their communications and interactions were recorded. They were likely to share their views on the AR-integrated teaching process so the community could be seen as a social network. The major teaching subject domains of the community teachers were science, chemistry, physics, geography, information technology, mathematics, and engineering. Participants had an average of 12.7 teaching years, and 60% of them were female. Their ages ranged from 25- to 55-year-old, with the average 38.8-year-old. This study also obtained the ethical approval from the selected university, and consents from all the participants.

The participants designed and developed AR-integrated STEM instruction to teach COVID-19, for example, by identifying student misconceptions and building 3D visual models. AR teaching was new to most of them and placed obstacles in their teaching. In the teaching process, students were required to use the visualized AR-supported digital textbook to understand the key concepts for SARS-CoV-2 prevention deeply through interactions with 3D visual models or videos under STEM activities. They were asked to join a teacher learning community to communicate and collaborate, share, and discuss their ideas and experiences with other participants. Since the participants' backgrounds were diverse, they should have different roles in the community, and their perceived support from others should vary.

In the learning community, there were two kinds of collaboration: online and offline. In the offline collaboration, teachers worked together in groups of three to five in weekly face-to-face group meetings for conducting an AR-integrated STEM lesson. In the online collaboration, the teachers joined any discussions of problems and issues at their convenience in an instant message system (i.e., WeChat). They shared their instructional designs, AR-integrated works, and student learning projects ideas in the system. Specific and scheduled planning activities were set for the participants. The teachers' communication and collaboration can be represented in a complex network.

There are four orders of barrier regarding teachers conducting AR-integrated STEM teaching, including first-order barriers about extrinsic obstacles (e.g., equipment obstacle: The AR apps for STEM may not work reliably on some older mobile devices), second-order barriers regarding intrinsic obstacles (e.g., superficial beliefs about technology: Teachers just view AR as a tool for the visualization of STEM learning), third-order barriers referring to management (e.g., distractions: Some apps or devices may sometimes distract the teacher's attention from AR-STEM learning), and fourth-order barriers related to the lack of design thinking (e.g., lack of design thinking: It is a challenge for me to adopt adequate mobile technology at the right time and in the right place to improve students' AR-STEM learning effectiveness). Therefore, this requires four orders of perceived support to overcome the corresponding barriers. To encourage teachers to overcome the corresponding barriers, this study developed the AR-integrated STEM teaching context to identify the relationships between teachers' roles and perceived support from the perspective of interactive content, which previous studies did not investigated.

3.2. Data collection

Fig. 1 shows how this study collect various to answer the three research questions. To answer RQ1, a questionnaire was used for the data collection on teachers' relationships in the community to explore different teachers' roles in the AR-STEM teaching community. To answer RQ2, a focus group interview, a questionnaire, and the digital system were used to collect data to investigate teachers' perceived support for overcoming barriers regarding AR-integrated STEM teaching. The interview consisted of four categories: first-order support, second-order support, third-order support, and fourth-order support; the questionnaire included two dimensions: active constructive and active destructive; and the system collected teacher's message. To answer RQ3, a multiple regression was conducted to analyze the relationships between the teachers' roles and perceived support for overcoming barriers to AR-integrated STEM teaching.

3.2.1. Questionnaires

A modified questionnaire from the past study (Lin et al., 2016) was used to collect data to identify the teachers' roles in the community. The original items include three types of interaction: trust relationship, consultant relationship, and exchanging informational relationship. The modified dimensions were developing trust, consulting research, and exchanging research information. First, "developing trust" is used to

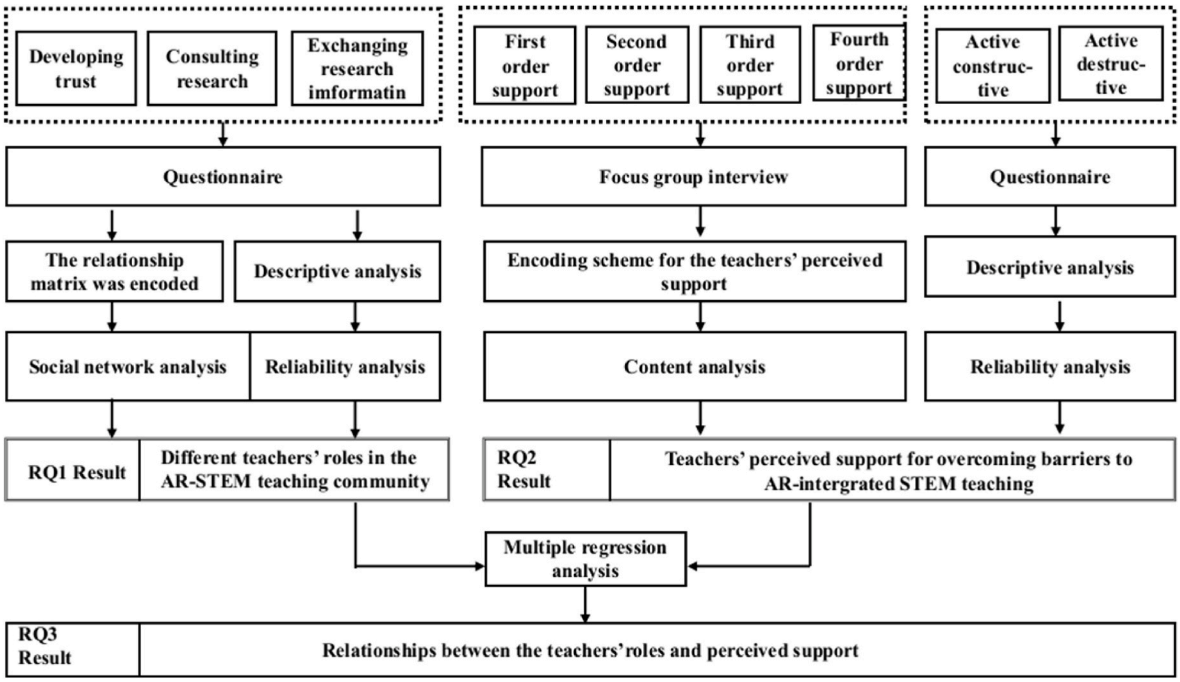

Fig. 1. Data collection and analysis.

examine the extent to which teachers were willing to share instructional resources and accept suggestions of others in the community; it includes five items. Measuring developing trust is important for helping to promote more effective pedagogical collaboration and knowledge sharing. Second, "consulting research" is used to assess the extent to which teachers prefer to communicate among members of the teacher learning community. Measuring consulting research provides a good indicator of whether community members are receptive to contributing and sharing expertise. The consulting research has four items and identifies the consultant targets. Third, "exchanging research information" is used to evaluate the extent to which members share and disseminate research information in the community. There is a need to observe the exchange of research information to identify the person the teachers want to share their information with. Exchanging research information dimension has three items. The three dimensions sample items are listed in Table 1.

Thus we adapted the items from Lin et al. (2020) to measure teachers' perceived support. The items had two constructs: active constructive (original Cronbach's alpha = .81) and active destructive (the variable's original reliability was α = 0.81), with high reliability. They adopted a 5-point Likert scale, with anchors ranging from *strongly disagree* (1) to *strongly agree* (5).

(1) An active constructive response means that a responder expresses excitement, enthusiasm, or a desire to participate in an event (i.e., with perceived support for beliefs about technology integration, I can effectively take advantage of a mobile device rather than be restricted).
(2) An active destructive response means that the responder is focused and involved, yet gives negative feedback (i.e., if the lesson is well-designed, students can be immersed in the AR-integration STEM learning process. However, my supervisor reminds me that everything has a negative side and that the lesson needs further improvement).

3.2.2. *Group interviews*

Twenty teachers were purposely selected for the interviews based on the SNA results as they played different roles in the network (Teacher 1–20). The interviewees could express how they perceived and gave support from/to teachers in the community. The interviews were conducted by a trained researcher and lasted 15–20 min (20 min on average). Furthermore, the interviews were audiotaped and then transcribed into text for content analysis. Sample questions from the interviews are listed as below.

1) From your point of view, what is AR teaching, and how can it facilitate STEM learning among students?
2) What do you think would be ideal AR-integrated STEM teaching? Describe your ideal teaching with short and brief sentences and explain why you said this.
3) What is your favorite part of AR-integrated STEM teaching support, and how does it help you address difficulties and barriers?
4) Do you face difficulties when conducting AR-integrated STEM teaching? If yes, please state them.
5) What are the main barriers you face while using AR for teaching STEM?

3.3. *Research procedure*

Fig. 2 shows the research procedures of this study, which include four stages. (1) **Determining objects and boundaries:** Teachers' roles and their perceived support for overcoming barriers to AR-integrated STEM teaching are complex and diverse. Communication and collaboration in the teaching community are crucial to removing these barriers. These kinds of interactions in the teaching community will form a complex network. In this study, the network boundary spanners of SNA contain online communications and real-world collaborations in teaching and research activities. (2) **Determining the relationships:** Network relationships between the members could be clarified by exploring and justifying forms of professional practice. The teachers' roles in the AR-integrated STEM teaching community were identified with a relationship matrix. Furthermore, the relationships between the teachers' roles and their perceived support for AR-integrated STEM teaching were determined with multiple regression analysis. With reference to Lin et al. (2016), we determined the typology for the interaction content as trust relationship, consultant relationship, and exchanging informational relationship. (3) **Collecting data:** This study

Table 1
Questionnaire on the relationship perspectives of the AR-integrated STEM teaching community.

Dimension	Item	1	2	3	4	...	52
Developing trust	Who was a cooperator in the teaching with you (e.g., papers, books, and reports)?						
	Who do you often work together with in the AR-integration STEM team?						
	With whom did you often design a research lesson?						
	With whom do you comment on members' cyberspace information with each other (articles, pictures, videos, and audio)?						
	In whose cyberspace have you left messages about AR-integration STEM teaching recently (articles, pictures, videos, and audio)?						
Consulting research	With whom do you have online contact information related to AR-integration STEM teaching? (For example, email, WeChat, blog, etc.)						
	To whom do you often chat about AR-integration STEM teaching (via email, WeChat, blog, etc.)						
	With whom do you discuss your AR-integration STEM teaching problems on the Internet (via email, WeChat, blog, etc.)						
	Whom do you ask for help when you have AR-integration STEM teaching problems in your teaching and research in the real world?						
Exchanging research information	To whom do you convey STEM instructional information via AR devices (via email, WeChat, blog, etc.)						
	To whom do you transmit teaching and research information on AR-integration STEM teaching in the real world?						
	To whom do you convey information on the Internet (via email, WeChat, blog, etc.)?						

used questionnaires and group interviews to collect data to see how the participants interacted in the community. (4) **Analyzing the data and drawing the results:** The data analysis included the SNA on the social network of teachers' roles in the AR-Integrated STEM teaching community, the content analysis for data from the focus group interview, and statistical analysis for the questionnaire.

3.4. Data analysis

Three different analyzes were used to identify teachers' roles and perceived support in the community and to explain their relationships.

To answer RQ1, **SNA** was used to analyze the data from the questionnaire to identify the teachers' roles in the community that are represented as nodes in the network through three steps. First, there are 52 columns on the right side of the questionnaire items in Table 1. The 52 columns of numbers represent the anonymity of the 52 teachers, a code for real names. When completing the questionnaire, teachers were asked to check off the 52 individuals who collaborated and interacted with AR-integrated STEM teaching in different items. Second, according to the existing literature, the data for each item of the three dimensions of the questionnaire was given equal weight in Table 1, and was weighted to obtain a relationship matrix. The matrix was derived from summing the relationship data collected from these 52 teachers in the same network. Third, UCINET 6.0 was used to analyze the relationship matrix in this study. The analysis generates the relationship matrix and analyzes the network's interpersonal structure (i.e., reflecting how teachers collaborated in the community). The matrix was encoded to represent the sender, receiver, frequency, and direction. Nodes of the same type (the same teacher role) in the network were weighted and combined with those having the same weight value. Moreover, a network-structure analysis with the matrix (i.e., the interpersonal structure and group interactions of the AR-integrated STEM teaching community were analyzed through social network analysis of the encoded matrix, resulting in a network structure diagram for the 52 teachers), centrality analysis (i.e., degree, closeness, and betweenness), and structural holes were used to capture the roles of teachers in the relational networks in Table 2.

Teachers' roles could be measured by key indicators, including the structural holes (SH), the larger trust network's structural holes (LTNSH), the degree of centrality (DC), and the higher degree of centrality in the trust network (HTNDC). An analysis of SH may help to understand that teachers with sufficient resources and the ability to share resources are expected to perform the role of a broker or channel between communities (Zhang et al., 2022). Analyzing LTNSH can provide insights into the broader structure of community interpersonal relationships, which is essential to influencing, mobilizing, and leading others to higher levels of achievement (Polizzi et al., 2019). It is important to identify DC to understand the central leadership in the teacher learning community with strong interactions and shared goals (Anspal et al., 2019). An analysis of HTNDC may distinguish teachers according to their central position in the digital learning environment (Yondler & Blau, 2023).

The mathematical functions to measure SH and DC are as follows.

Burt (1992) indicated the importance of addressing the issue of constraint to measure the presence of SH. To analyze the constraint in the networks of the AR-integrated STEM teaching community, this study defines the constraint with the following mathematical function:

$$c_{ij} = \left(\frac{|\zeta(i) \cap \zeta(j)|}{|\zeta^*(i)|}\right)^2$$

Where the network of teacher ego i is directly or indirectly invested in a relationship with some other contact j, In this mathematical function, $\zeta(i)$ is the set of all opposite-class contacts of i in the network of the AR-integrated STEM teaching community, and $\zeta^*(i)$ the sum of the dyadic constraint on all of a vertex's ties. Pendants are nodes that should be excluded from the calculation because they only connected to one other node.

Milaković et al. (2008) noted that DC for each individual that can be calculated as the sum of the actual valued tie strengths of an individual. In this study, the DC could be measured with the following mathematical function：

$$\text{degree}_u = \sum\nolimits_{v \in V} C_{uv}$$

In this function, C could be defined as the entire network of the AR-integrated STEM teaching community. V is represented as the set of directors contained in C. The centrality of node u is constructed by summing the number of links that each node has.

The difference between measures that were and were not in the larger trust network is shown below. First, SH was measured by how teachers with sufficient resources play a broker role. Furthermore, the measurement of LTNSH could help us deeply understand teachers' roles. Specifically, (a) Teachers in LTNSH have more teaching resources and greater access to information, enabling them to act as "gatekeepers" to a

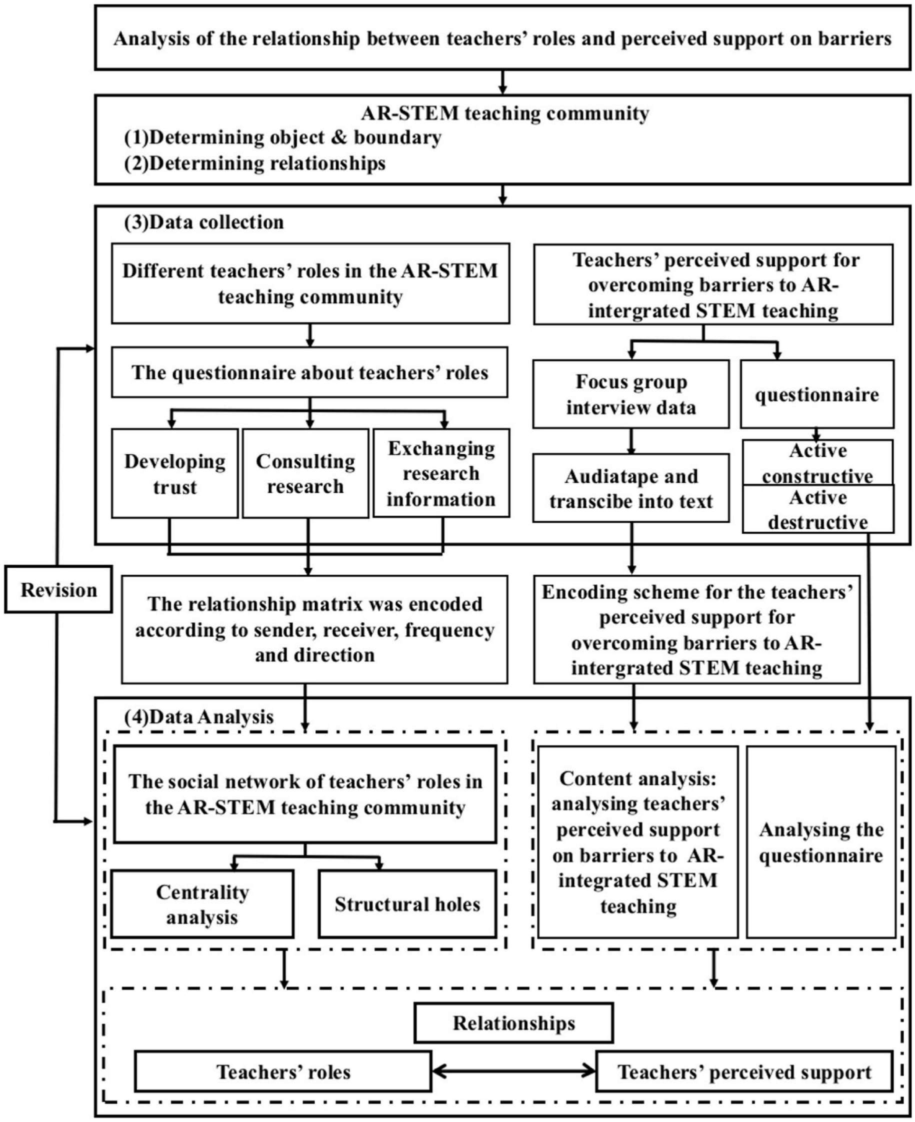

Fig. 2. The research procedure.

significant degree, as well as being the key to the dissemination of resources in the trust community; (b) teachers connected to LTNSH have fewer opportunities to share teaching resources and experiences with other members of the AR-integrated STEM teaching community, and are more dependent on communication mediators. With the measurement of LTNSH, members of the AR-integrated STEM community would be supported with multi/interdisciplinary education resources, distinguishing it from just measuring SH. To examine whether there is an effect of LTNSH on teachers' perceived support for AR-integrated STEM teaching through teachers' roles in the network, it is important to extract the trust relationship network structural holes because the interaction between teachers in the AR-integrated STEM teaching requires trust, which is the most fundamental. Trust is the key to driving teachers to sustained collaboration for AR-integrated STEM teaching. In designing the AR-integrated STEM project about the robot drama Hamlet, there would be several barriers to combining robot programming and a theatrical plot when there is only an IT teacher or a literature teacher. Via a larger trust network (i.e., LTNSH), the teachers' group would have been able to access sufficient interdisciplinary (IT and literature) resources and take the project from design to display innovatively. Besides, through a larger trust network, experts in the community were expected to provide various forms of perceived support to others.

Since it is unclear what kinds of teachers' perceived support are most beneficial in AR-integrated STEM teaching community, this study aims to better reveal the critical perceived support from community members to address challenges when using AR to support STEM learning. To answer RQ2, it is wise to select qualitative content analysis for identifying different teachers' perceived support regarding overcoming barriers in the AR-integrated STEM teaching, then the capacity of content analysis is systematically compared and categorized interview data in depth. The teachers' interaction content was collected and coded from different data sources (i.e., interview record, count = 156, 59.50 %; Content of teachers' messages on AR-integrated STEM teaching system, count = 106, 40.50 %). This study used the teachers' perceived support for overcoming barriers to AR-integrated STEM teaching as a scheme to code the data. An encoding process was designed to analyze the content of teachers' perceived support for overcoming barriers to AR-integrated STEM teaching in different groups, which was developed using Chen et al.'s (2022) hierarchical model. This study focused on four orders, including first-order barriers about extrinsic obstacles (FO), second-order barriers regarding intrinsic obstacles (SO), third-order barriers referring to management (TO), and fourth-order barriers related to the lack of design thinking (DO) in the AR-integrated STEM teaching. Two researchers, an educational technology professor and a

Table 2
The classification of the teachers' roles.

Teachers' Roles	Definition	Examples of Teachers' Roles in the Community
Structural Holes (SH)	The structural holes imply a broker between contacts in the social network of the AR-integrated STEM teaching community, where teachers on either side of the SH have access to shared knowledge and resources.	Teachers in the structural hole are more likely to broker the information flows between groups of teachers and have a greater mediating advantage to share multi-interdisciplinary knowledge and resources for teaching and learning with other AR-integrated STEM teaching community members.
Larger Trust Network's Structural Holes (LTNSH)	The relatively larger structural holes that teachers need to broker for connecting different AR-integrated STEM teaching community group members in the trust network.	Teachers with larger structural holes in their trust network have fewer opportunities to share teaching resources and exchange experiences with other groups of AR-integrated STEM teaching community members. Accordingly, there is a need to uncover the mechanism of the structural holes to connect multi-interdisciplinary teachers in different positions.
Degree Centrality (DC)	The degree of teachers becoming central in the AR-integrated STEM teaching community relates to tacit knowledge transfer.	Teachers with central roles have higher communication ability and cognitive levels to interact with other teachers, acquire tacit knowledge, and manage tasks related to the learning environment as leaders in the AR-integrated STEM teaching community.
Higher Degree Centrality in the Trust Network (HTNDC)	Teachers prefer to direct and lead other AR-integrated STEM teaching community members in a central position in the trust networks.	Teachers, as highly core members, establish common goals in a trusted AR-integrated STEM teaching community to promote interaction among other members and facilitate the transfer of tacit knowledge in the network with trust.

postgraduate student, first read the scripts, identified different types of perceived support for overcoming barriers, and then assigned descriptive codes accordingly. They discussed and merged the codes into orders. The categorization agreement was 0.92 (Cohen's kappa) between the two researchers. When the interview data did not reach the researchers' agreed-upon categorization, the researchers discussed the interview data until they reached a consensus. For instance, codes relating to "resistance to AR use" and "beliefs about AR-integrated STEM teaching" were merged into the "intrinsic obstacles" order. Examples of the teachers' qualitative responses were coded as first-order support, second-order support, third-order support, and fourth-order support. These examples are presented in Table 3.

In addition, this study carefully examined the interview data and extracted representative responses for in-depth discussion. Twenty teachers with different roles participated in the focus group interviews and provided key information in the trust network. The interview data were fully transcribed by a trained research assistant, and then examined and analyzed by two researchers through extensive discussion.

The 20 interviewees were divided into the following four categories for this study: (a) Group founder and leader. These teachers played a leadership role in organizing and guiding the activities within the community, providing direction and vision. (b) Experienced core member. These teachers had previously served as project leaders and may have since transitioned to other roles, such as important teaching and research staff responsible for helping to solve new teaching

Table 3
The encoding scheme for the teachers' perceived support for overcoming barriers to AR-integrated STEM teaching of hierarchical content analysis levels.

Level	Definition	Example items of perceived support for overcoming barriers to AR-integrated STEM teaching
First-Order Support	Support for overcoming extrinsic obstacles for teachers, including equipment, enough features in student devices, and organizational support for technical problems during a time-consuming content development phase.	When I have perceived support for equipment, it is easier to use AR apps for STEM teaching because the equipment works reliably.
Second-Order Support	Support for overcoming intrinsic obstacles for teachers, such as beliefs about AR-integrated STEM teaching, beliefs about technology, resistance to AR use (Sırakaya & Alsancak Sırakaya, 2022), and openness to change.	When I have perceived support for beliefs about technology integration, I can effectively take advantage of a mobile device rather than be restricted.
Third-Order Support	Support for management, such as management of avoiding distractions and cognitive loads caused by AR.	When I have perceived support for management to avoid distractions caused by AR, I can carry out the STEM course smoothly when students may be overly attracted to the mobile AR device.
Fourth-Order Support	Support for overcoming a lack of design thinking, such as providing meta-cognitive scaffolding and experimental support for AR inquiry-based learning activities (Ibáez & Delgado-Kloos, 2018).	When I have perceived experimental support for AR inquiry-based learning activities, I am capable of adopting adequate mobile technology at the right time and in the right place to improve students' learning effectiveness when students could not be immersed in the AR-integration STEM learning process.

problems. They possessed valuable insights and experience from their prior involvement. (c) New core member. These teachers had recently taken on the role of project manager and facilitator. They brought fresh perspectives and ideas, creating an optimistic connection to the growth and development of the community. (d) Periphery actor. This category includes teachers with limited involvement within the community, but their perspectives and contributions were still valuable within the trust network. Teachers in different roles interact with each other and collaborate to promote AR-STEM teaching.

To answer RQ3, a multiple regression analysis was conducted to analyze the relationships between the teachers' roles and perceived support for overcoming barriers to AR-integrated STEM teaching. A total of 52 teachers were selected for the multiple regression. The independent variables in this study were teachers' roles in the teaching community (i.e., DC, SH, HTNDC, and LTNSH). The dependent variables were teachers' perceived support for overcoming barriers to AR-integrated STEM teaching (i.e., FO, SO, TO, and FO). A series of stepwise (multiple) regression analyses were implemented to evaluate the relationships using IBM SPSS software (version 26). In the multiple regression analysis process, the mathematical function compares average values of y in the upper and lower quantiles of x. The x here refers to the independent variable mentioned above, and y refers to the dependent variable mentioned above in this study. First, this study conducted a linear regression of y on x based on n data points and compared the least-squares estimate to a simple difference of the mean of data values y in the upper and lower quantiles of x. Second, thresholds x^{lower} and x^{upper} were established to represent the (fn)th and $((1-f)n+1)$th order statistics of x. The predictor was discretized by utilizing the chosen order statistics. Third, the linear relationship between y and x by the simple comparison. Finally, the mathematical function was used to calculate the ratio and compare it to the least squares estimate.

4. Results

4.1. Teachers' roles in the AR-integrated STEM teaching community

To answer RQ1, SNA was conducted to examine teachers' roles in centrality measures and structural holes. The centrality measures include degree, closeness, and betweenness centrality. Degree centrality is the number of points directly connecting to a point in a network, which can be used to find the core nodes in a network with their attributes. Closeness refers to the sum of the shortest distance of a node to other nodes; the smaller a closeness value is, the more a point is in the core of the network. Betweenness measures the extent to which a node is a "bridge" to other nodes. Since this matrix (i.e., the encoding data for community relationship analysis for SNA) belongs to an undirected valued graph, a calculation of the betweenness of multi-valued networks cannot be carried out in UCINET's existing algorithms. Through the SNA, a network sociogram is obtained, which is shown in Fig. 3. By using the NetDraw module of UCINET, teachers in the social network were denoted as nodes. A node represents individual learning community members, such as teachers, leaders, or facilitators. This represents the relationships between teachers' roles and their barriers regarding AR-integrated STEM instruction. From Fig. 3, we may conclude that the core nodes in the structure interconnect with strong links without an isolated node, indicating that the members interacted closely in the teacher learning community. Nodes 1, 2, 3, 4, 5, 6, 8, 9, and 10 formed a cohesive subgroup with Node 5 as the core, while Nodes 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 21 formed a second cohesive subgroup with Node 16 as the core. Both cohesive subgroups are components of the AR-STEM teaching community in this study. Moreover, research has revealed that AR-STEM teaching community, as an organizational structure, can better promote teachers' interactive connection and use of social capital (Demir, 2021). A detailed analysis of the features of the network structure and nodes is provided below.

Teachers' roles may be determined by measuring the structural holes (SH), the larger trust network's structural holes (LTNSH), degree centrality (DC), and the higher degree centrality in the trust network (HTNDC). A detailed analysis of the features of the network structure and nodes is provided below. SH means a broker between contacts in the network where teachers on either side of the SH have access to share knowledge and resources. Nodes 5, 6, and 8 were the top three nodes from the perspective of SH in the network, revealing that they served as a "broker" for the teacher learning community. In other words, those with higher SH values were more likely to access the resources available in the network.

LTNSH is a broker which connects different groups of teachers in the larger trust network. Node 8 had the highest value of LTNSH, indicating that he connected with teachers in the subgroups and shared more resources and knowledge with different AR-integrated STEM teaching community group members than other community members. After the interview, it was shown that Node 8 was a teaching and research staff in the community. He built strong trusting relationships with other teachers and shared his inner beliefs of AR-integrated STEM teaching. Teachers with great relationships had similar goals for the future and a shared comprehension of STEM teaching and learning.

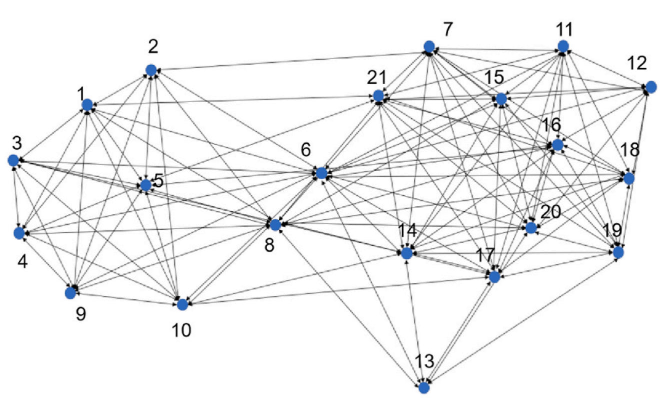

Fig. 3. Network sociogram.

The number of points directly connecting to a point in a network (DC) is defined as teachers who are central in their AR-integrated STEM teaching community's existing networks. Nodes 15 and 20 had slightly higher values than the rest of the network, indicating that they interacted more actively with different teachers in the community. The interview revealed that Node 15 was an administrative leader, while Node 20 was a resource sharer. They both played a similar central role in the community.

Teachers with a higher degree of centrality in the trust network (HTNDC) preferred to direct and lead others in a central position in their trust networks. Regarding the problems in the AR-integrated STEM teaching process, teachers with great relationships were more receptive to one another than those without, and they collaborated to solve challenges and accomplish objectives by sharing resources.

Regarding the teachers' responses to the questionnaire about teachers' roles, the network of teachers' roles in the AR-integrated STEM teaching community had a mean score of 4.25 (S.D. = 1.12), meaning that the weighted number of links that each person had on average was 4.08. Regarding the teachers' idea-exchange interactions in the real AR-integrated STEM teaching and collaboration activity, the sample of teachers had network centrality (HTNDC) in their networks with a mean score of 3.65 (S.D. = 1.19), meaning that the weighted number of links that each person had on average was 3.65 in the network of teachers' roles in the AR-integrated STEM teaching community. Nodes 5, 16, and 17 were the top three nodes from the perspective of HTNDC, and they also had a high number of weighted links. These three teachers also regularly shared AR teaching resources with other teachers in the online community, indicating that teachers with higher HTNDC values were more likely to interact with other teachers. Thus, these findings support the belief that teachers who play more central roles in the AR-integrated STEM teaching community are accepted.

4.2. Teachers' perceived support for overcoming barriers to AR-integrated STEM teaching

In this section, the results are divided into two main parts. The first part consists of results from content analysis of what social networks are like. The second section reveals the results of how teachers received mutual support in the network and how teachers made sense of the support they perceived, which reflects teachers' connections within the network structure.

4.2.1. Result of content analysis

The results are shown concerning research question 2. Table 4 reports the quantitative process's support data based on the distribution of the 262 coded data gathered over 1 week synchronously and asynchronously regarding the AR-integrated STEM teaching system.

Table 4
The descriptive data on the teachers' perceived support for overcoming barriers to AR-integrated STEM teaching.

Variable	Frequency	Mean	SD
FO	76	1.98	3.33
SO	52	1.11	1.49
TO	50	0.66	1.19
DO	84	0.49	1.12

Note. FO: perceived support for overcoming first-order barriers; SO: perceived support for overcoming second-order barriers; TO: perceived support for overcoming third-order barriers; and DO: perceived support for overcoming fourth-order barriers.

Based on the results shown in Table 4, the teachers on average delivered 1.11 ideas or information for social purposes and 5.57 ideas in total in the AR-integrated STEM teaching and collaboration activity. Moreover, one-third of the teachers (29%) engaged in perceived support for overcoming first-order barriers by asking and providing details about extrinsic obstacles (FO), whereas perceived support for overcoming second-order barriers regarding teaching beliefs (SO) occupied 20% of the participants, respectively. Higher phases of perceived support for overcoming barriers were also found in this study. The teachers devoted 19% of their discussion to perceived support for overcoming third-order barriers (TO) in total and 32% of their discussion to perceived support for overcoming fourth-order barriers (DO) in total. The discussion on higher phases of the knowledge process indicated that using an AR-integrated STEM teaching system in the teaching community with sufficient support, such as leading questions for each group, facilitates teachers' AR-integrated STEM teaching and collaboration. The interview feedback also provided an explanation of the teachers' perceived support for overcoming the first-to fourth-order barriers. Thus, the teachers showed more perceived support for overcoming barriers to AR-integrated STEM teaching statistically for fourth-order barriers, which in turn might form final themes.

Table 3 shows situational excerpts for each order. **In terms of FO,** extrinsic obstacles support (e.g., equipment and devices) could be accessed via face-to-face consultation and collaboration among community members, which can effectively overcome the barrier to collecting online interaction data. By leveraging enough features on iPad devices, the successful collection of students' online interaction data becomes possible in AR-integrated STEM courses. **In terms of SO,** community members played a crucial role in supporting teachers to overcome intrinsic obstacles and insecurity related to the implementation of AR technology during the challenging COVID-19 period. These community members who were skilled and reputable in AI education, served as role models for others and improved their beliefs about AR-integrated STEM teaching. **In terms of TO**, experienced teachers can proactively guide novice teachers by explaining the organizational rules face-to-face and offering support in instructional management. This collaborative effort ensures a more efficient and well-managed AR-integrated STEM classroom environment, avoiding distractions caused by students' excessive focus on AR resources. **In terms of DO**, when it comes to designing AR-integrated STEM projects, teachers potentially struggle with barriers to interdisciplinary instructional design. Teachers of various disciplines within the trusted community can offer valuable resources and assist in adding scaffolding and optimizing instructional designs in online and face-to-face environments.

4.2.2. *Result of interview analysis*

An analysis of the transcripts of the interviews with 20 teachers provided a clear picture of teachers' perceived support for overcoming barriers to AR-integrated STEM teaching. The characteristics of interview participants were shown in Table 5. These teachers were asked to describe their perceived support in AR-integrated STEM teaching. Interview data reflected that teachers in different roles have perceived different levels of support. This study found that the group founder and leader, experienced core member, new core member, and periphery actor reported participation rates of 86.12%, 82.20%, 78.6%, and 58.9% of all interview participants, respectively. These results reveal that compared with other teachers' categories, participation rates of Teachers 9, 15, and 20 who served as group founders and leaders are likely to be larger in taking part in the AR-integrated STEM teaching activities. These suggest that the teachers who have values of HTNDC in their characteristics regarding the result of SNA were more central in a trusted AR-integrated STEM teaching community than other members.

Table 5
The characteristics of interview participants.

Teachers' categories	Teachers' number	Participation rate	Teachers' characteristics regarding the result of SNA
Group founder and leader	9, 15, 20	86.12%	Top 3 values of HTNDC
Experienced core member	1, 2, 5, 8, 18,19	82.20%	The values of LTNSH, DC are both relatively high
New core member	3, 6, 10, 12, 14, 17	78.6%	The values of SH, DC are both relatively high
Periphery actor	7, 4, 11, 13, 16	58.9%	The values of SH, LTNSH, DC and HTNDC are significantly lower than others

Note. the structural holes (SH), the larger trust networks structural holes (LTNSH), degree centrality (DC), and the higher degree centrality in the trust network (HTNDC).

According to the interview, regarding support of technology integrated with instruction, Teacher 6, a new core member, mentioned:

> I am an English teacher. I am not very familiar with technologies and interdisciplinary teaching approaches. I participated in several face-to-face training sessions and meetings where Teacher 15 taught me how to use different technologies for AR-integrated STEM teaching. These sessions are great for learning new skills, knowledge, and emotional interaction. Since I picked up things quickly, I was invited to conduct similar training for other teachers in need.

A periphery actor, Teacher 11, he said that he frequently accessed pertinent teaching resources from the AR-integrated STEM teaching system, including videos of community teachers' classes and AR courseware designed for their instruction. These user-friendly resources can be readily incorporated into my courses with minimal or no modifications. They have greatly aided me in quickly adapting to and implementing AR-integrated STEM teaching. Hence, he is deeply appreciative of the teachers within the community who generously share these online resources.

These indicated that teachers could receive first-order support and enhance the quality of AR-integrated STEM instruction by receiving help from other teachers in face-to-face and online communication.

Teachers 2, 8 and 5 were experienced core member teachers. As for the support of belief and literacy about AR-integrated STEM instruction, Teacher 2 said that in reality, numerous teachers possess great capabilities. Nevertheless, they may experience a depletion of mental energy when confronted with consecutive tasks, leading them to consider giving up. What they truly require is an outlet to share their mental state, seeking empathy or spiritual support from fellow teachers. It is crucial for them to establish trust among each other, ensuring that their confessions are not misconstrued as mere complaints. When teachers within the community encounter frustration, he typically offers words of encouragement or lend a listening ear to their reflections.

Teacher 8 said "In the community, I propose the notion of flexible adaptation in AR-integrated STEM teaching, … as it empowers teachers to excel by adjusting to various classroom scenarios. Consequently, we are expected to improve the connections between different disciplines." "It is difficult for teachers to re-learn unfamiliar knowledge, especially for teachers who have worked for more than 10 years… Thus, I need teachers with leadership to address this issue in teaching AR-integrated STEM courses", Teacher 5 said. These comments suggested that teachers could obtain second-order support, which improved their teaching mental energy and interdisciplinary competence through community interaction and sharing.

When it comes to the support to manage the classroom and decrease distractions, Teacher 14, a new core member in the community, said:

> Students may be attracted to AR devices. Therefore, it is important to make students focus on the STEM learning project rather than being restricted by the devices. In fact, teachers need to keep abreast of the latest developments. It is important to guide students to fall in love with AR-STEM learning. I have learned some tips from the teacher community to encourage students to focus on learning content.

Besides, Teacher 1, who was identified as an core member, said that among one of the crucial topics in our AR-STEM project, they employ an AR-enhanced context involved in the simulation of using firefighting robots to escape from a fire accident:

These firefighting robots were a powerful tool for students to experience unexplored, potentially dangerous tasks. However, the students were very crazy about this activity because this was very interesting. To decrease distractions caused by the AR-enhanced activity, other teachers from the community have helped me improve this course from the classroom management perspective. Therefore, we collaborate to make students focus on learning the corresponding knowledge.

These comments highlighted how teachers gained valuable support in managing the classroom, decreasing distractions, and reminding students to focus on the topic in their AR-integrated STEM teaching practices through support from different teachers, which related to the third-order support to address barriers relating to management.

In addition, teachers also talked about the support to generate better ideas for solving complex problems in practice, organize other teachers for design thinking, and create innovative learning materials, pedagogy, and curricula. For example, Teacher 20, a university expert in AR-integrated STEM, was identified as having the orientation of founder of the group and leader. He was able to provide various forms of perceived support to others in the network, including theoretical and practical teaching guidance on artificial intelligence education. Teacher 20 pointed out that teachers need to support each other in the community to enhance their design thinking. He said:

> We will organize other teachers to join in diagnosis activities for design thinking. In this process, we work online together in our system to identify and solve some teaching issues in the implementation of AR-STEM courses. After teachers shared their instructional design project of Hamlet's STEM Robot stage play, the teaching and research staff could rely on some design thinking to optimize teaching. For example, we consider adjusting users' emotions by analyzing some STEM project-making problems caused by the different levels of students. In this process, we can generate better ideas for making the entire instructional design more effective and interesting.

Teacher 9 was also a founder of the group and a leader. He said that he is a designer when working and teaching in an AR-integrated STEM community to create innovative ideas:

> I have designed new learning materials and pedagogies. In addition, I am involved in engaging our community teachers to develop and create various innovative STEM learning activities. I believed that I was born to teach STEM. When working with other teachers, I could gradually forget everything.

These comments suggested that teachers in the community could their design thinking and successfully integrate AR technology into their STEM instruction with the support of other teachers, which concerns the fourth-order support to address barriers related to the lack of design thinking.

Based on interview data, the study demonstrated that teachers in different roles perceived different levels of support within the community, including support of technology integrated with instruction, support of belief and literacy about AR-integrated STEM instruction, support to manage the classroom and to decrease distractions, support to generate better ideas for solving complex problems in practice, and so on. For instance, it can be seen that in the network, teachers engaged in many AR-STEM teaching activities, such as hosting online meetings where teachers share how to better use equipment in AR-integrated STEM education, conducting face-to-face training to improve teachers' beliefs about AR-STEM teaching with excellent teaching cases from community teachers, organizing teachers to study the classroom management curriculum developed by experts on the AR-integrated STEM teaching system, holding seminars where some teachers teach offline and experts listen to the lessons online and give feedback later, and so on. Teachers in different roles collaborate to promote AR-STEM teaching. For example, Teacher 10 stated that he perceived support of technology integrated with instruction, allowing him to provide a blended online and offline AR-STEM course, a task he had not previously been able to accomplish. Teacher 12 mentioned that she was able to learn how to creatively design the instructional process by interacting with other experienced core members in the network. These suggested that teachers in the community found that the network facilitated their collaboration regarding AR-STEM teaching.

In addition, there are quotes from the interviews which illustrate the interaction between different roles of teachers that reflect the structure of the social networks. For example, Teacher 19 said:

> I think the interaction and collaboration in the AR-STEM project did stir some creativity. Take the novel coronavirus 3D model as an example. Teacher 9 is a leader, and he contributes more and integrates everyone's ideas or thoughts, which I am not good at. Teacher 16 provides me with many ideas or references to consider. Besides, he is more creative because he has many ideas and interactions with others. He can say "Hi" even to unfamiliar people on the road, and he has interest in a lot of stuff. I am an idea creator, too, and Teacher 5 is mainly working on the programming to make my ideas come true. When I need support, I can seek it through our project team. I believe the whole AR-STEM community can be a great way and resource to complete the cross-disciplinary task of AR-STEM teaching. And I can get various kinds of support from different disciplinary teachers. I would like to continuously conduct projects collaboratively with others. There are things that I cannot work out alone. Thus, I want to work in the community.

This quote from Teacher 19 provides a description of how the teacher interacted with others in their social networks. This could be a valuable supplement to illustrate the connections between a node's location in the network (see Fig. 3), which revealed that Nodes 5 (i.e., teacher 12) and 16 (i.e., teacher 9) were the primary leaders in terms of providing teaching resources and research resources, respectively.

4.3. The relationships between the teachers' roles and their perceived support for AR-integrated STEM teaching through regression analysis

The hypothesis predicted relationships between the teachers' support and their roles in the AR-integrated STEM teaching community through stepwise regression analysis. Regarding research question 3, our analyses in Table 6 indicated that the larger the AR-integrated STEM teaching community's structural holes (SH), the more support was achieved for AR-integrated STEM teaching and collaboration (SO-DO); similarly, the larger the trust-network structural holes (LTNSH), the more support was achieved for AR-integrated STEM teaching and collaboration via asking and answering questions regarding beliefs (SO) and design thinking (DO). Specifically, SH can significantly and positively predict SO ($B = 0.35$, $\beta = 0.34$, $p < 0.01$, $R^2 = 0.313$), TO ($B = 0.49$, $\beta = 0.47$, $p < 0.01$, $R^2 = 0.242$), and DO ($B = 0.76$, $\beta = 0.57$, $p < 0.01$, $R^2 = 0.216$). In addition, SO ($B = 0.72$, $\beta = 0.39$, $p < 0.01$, $R^2 = 0.468$) and DO ($B = 0.22$, $\beta = 0.20$, $p < 0.05$, $R^2 = 0.292$) can also be

Table 6
The relationships between teachers' roles and their perceived support.

Variable	SO	FO	TO	DO
DC	−0.05	−0.04	−0.14	−0.25
SH	0.05 **	0.52	0.01 **	0.15 **
HTNDC	0.43 **	0.32 *	0.36 *	0.37 *
LTNSH	0.03**	0.08	0.31	0.41 *

Note. DC: degree of centrality; SH: structural holes; HTNDC: teachers who have a higher degree of centrality in the trust network; LTNSH: the larger trust network's structural holes; **p < 0.05; **p < 0.01.*

predicted by LTNSH. This finding may suggest that teachers who play the role of brokers (with large structural holes) who connect different groups of people in their existing teaching community networks, were found to share knowledge and resources on AR-integrated STEM teaching with other group members. Interestingly, compared to the brokers in the existing AR-integrated STEM teaching community network, the teachers with larger structural holes who connected different groups of teachers in the trust network performed better regarding design-thinking support for overcoming barriers. This shows that even though their role was maybe the same as that of a broker, the role may associate more and perform better at different levels of perceived support for overcoming barriers because of the differences between the existing AR-integrated STEM teaching community network and the trust network. This means that the hypothesis in this study was supported. There is a significant relationship between the teachers' roles and perceived support for overcoming barriers to AR-integrated STEM teaching.

Besides, the higher degree centrality in the trust network (HTNDC) could positively explain the FO ($B = 0.42$, $\beta = 0.41$, $p < 0.01$, $R^2 = 0.192$), SO ($B = 0.26$, $\beta = 0.25$, $p < 0.05$, $R^2 = 0.317$), TO ($B = 0.43$, $\beta = 0.35$, $p < 0.05$, $R^2 = 0.193$), and DO ($B = 0.76$, $\beta = 0.57$, $p < 0.05$, $R^2 = 0.287$). As for the teachers who had higher degrees of centrality in their trust networks (HTNDC), they were correlated with attaining more support for overcoming FO barriers with respect to asking and answering questions about details, intrinsic obstacles to teachers' STEM teaching, classroom management obstacles, design thinking skills, and disposition barriers to AR-integrated STEM teaching. However, the teachers who are central to their existing networks (i.e., trust networks, consultant networks, and exchanging information networks) had no statistically significant relationships with each dimension of their perceived support (i.e., SO, FO, TO, and DO); see Table 6. The results imply that whether teachers played roles with a higher degree of centrality in the trust network was not related to their perceived support to overcome the corresponding barriers, including first-order barriers about extrinsic obstacles (FO), second-order barriers regarding intrinsic obstacles (SO), third-order barriers referring to management (TO), and fourth-order barriers related to the lack of design thinking (DO) in the AR-integrated STEM teaching.

5. Discussion and conclusions

This study uncovered the importance of teachers' roles and perceived support in the teacher learning community for overcoming barriers when designing an AR-integrated STEM teaching community.

Responding to RQ1, this study noted teachers' roles in the teacher learning community for AR-integrated STEM instruction. Specifically, teachers' roles consist of DC, SH, HTNDC, and LTNSH, among which each fulfils its own purpose simultaneously as the AR-integrated STEM community evolves. On one hand, SH and LTNSH are associated with resources and knowledge sharing in different trusted networks. On the other hand, DC and HTNDC could interact actively with other members in the existing and trusted networks, leading to a close connection with the community members. Therefore, DC and HTNDC could be regarded as the roles that need more attention in the AR-integrated STEM community, as they were potential leaders and facilitators in their networks when they had adequate perceived support. In line with previous research (Lin et al., 2016), they showed that teachers who play more central roles were more likely to have adequate educational resources, which connect to the guidance given, strong interactions, and the sharing of resources in the teachers' community. In addition, this study revealed that the social network of the AR-integrated STEM teaching community is the main channel for exchanging learning resources and knowledge, and it plays the role of supporting equipment and provides social support for distributed teachers. For example, a teacher with excellent performance in a certain field will be encouraged to help weak or underperforming teachers. The study's results align with previous research, which showed that teaching in a community helps relieve teachers' anxieties because peers and experts support new teaching strategies (Jho et al., 2016). AR has become increasingly common in STEM education (Ibáez & Delgado-Kloos, 2018).

Some barriers to AR-integrated STEM teaching were also emphasized (Sırakaya & Alsancak Sırakaya, 2022). In the context of this study, teachers are not particularly familiar with AR-integrated STEM teaching or need a social network of the AR-integrated STEM teaching community to find ways to solve barriers. They must try to use the solutions in teaching practice. Furthermore, these teachers benefit from the opportunity to implement their AR-integration STEM lessons successfully. They work together to achieve common success, integrating them into their social relationships. At the same time, although the knowledge is distributed, it can still be shared, which shows the supporting role of the AR-integrated STEM teaching community's social network. This study found that the extrinsic obstacles support (e.g., equipment and devices) could be accessed through community cooperation and resource sharing. A previous study revealed that teachers would require more assistance to get first-order support and become proficient in using the new technology (Kopcha et al., 2012). In terms of the second-order support, some teachers in the community helped improve members' beliefs about AR-integrated STEM instruction, such as supporting teachers to overcome the intrinsic barriers to AR technology implementation during the challenging COVID-19 period. In line with previous research (Jho et al., 2016), they showed that experienced teachers helped the teachers get second-order support and become familiar with new approaches to interdisciplinary teaching. As Chen et al. (2022) highlighted, classroom management could be a usual barrier to technology-integrated instruction, leading to cognitive loads. The third-order support could be accessed by a well-managed AR-integrated STEM classroom environment. The fourth-order support could be enabled by providing meta-cognitive scaffolding and pedagogical support to improve instructional designs of AR-integrated STEM teaching. Lin et al., 2023 noted that teachers' technology integration teaching needs more educational training, support, and meta-cognitive scaffolding to engage them in design thinking practices. Compared with the previous studies, which only noted the importance of different teacher roles concerning multi-interdisciplinary (e.g., Ma et al., 2016) and technological integration (e.g., Kopcha, 2012) in their learning community, one of the major significances of this study is that it proposes a theoretical framework that reveals teachers' roles in the teacher learning community, and indicates how leaders strengthen teachers' professional development for AR-integrated STEM education by providing perceived support from the perspectives of four orders: (1) to support teachers who need to overcome first-order barriers to extrinsic obstacles, the multi-interdisciplinary community leader could provide sufficient resources for helping others solve technological integration problems; (2) teachers with second-order barriers regarding intrinsic obstacles should be supported with psychological help and positive affective feedback to strengthen their beliefs and resistance to AR-integrated STEM teaching; (3) to support teachers with third-order barriers referring to classroom management, the community should teach the teachers how to avoid distractions and reduce cognitive loads caused by AR technological integration; and (4) teachers with fourth-order barriers related to the lack of design thinking should be assisted with meta-cognitive scaffolding and pedagogical support for improving the quality of their AR-integrated STEM teaching.

Further, as a response to RQ2, it could be concluded that teachers' perceived support involved the discussions and collaborative activities in the AR-integrated STEM community. This study revealed that the significance of teachers' perceived support for overcoming barriers in AR-integrated STEM teaching was directly embedded in the activity level rather than perceived support for overcoming barriers in AR-integrated STEM teaching. Studies have shown that collaboration and interactions in a community can increase members' sense of efficacy (Arici et al., 2019). A professional learning community can be a powerful method of enhancing the pedagogical content knowledge and collective knowledge of STEM teachers (Vossen et al., 2020). The teachers' knowledge development can be attributed to their perceived support from professional learning-community activities, such as post-lesson discussions, peer verbal persuasion, and co-designed lectures. In the AR-integrated STEM teaching and collaboration process, it is useful for teachers to positively share resources and knowledge to foster teaching because of the knowledge distributed in the AR-integrated STEM teaching community. Eventually, the final themes derived from the qualitative interviews with the content analysis, which consisted of four levels of teachers' perceived support for overcoming barriers, may provide useful ideas for developing the teacher professional development framework and facilitating education.

In response to RQ3, the multiple regression analyses showed that the teachers' roles were significantly predicted variables in the perceived support for overcoming barriers to AR-integrated STEM teaching, except for the correlation between DC and all the support (i.e., SO, FO, TO, and DO). Unlike a previous study which only noted the importance of DC and SH in the network to shared knowledge and resources for teachers (Demir, 2021), this study revealed that if teachers would like to perceive more support for overcoming barriers to AR-integrated STEM teaching, they may recommend to play roles in structural holes to become brokers for connecting different groups, rather than playing central roles to become bridges for interaction with other teachers. Previous studies emphasized that participation in social networks is beneficial to teachers' social capital related to teaching outcomes (Demir, 2021; Lin et al., 2016). Social capital offers insights into the resources that an actor has access to by examining the social relationships between others in a network, which may eventually support or constrain individual actions (Daly et al., 2021). This study further supports and extends this notion regarding in the context of AR-integrated STEM. Teachers should interact and collaborate more with other members as they exchange complex and tacit knowledge and sustain commitments to the community (Baker-Doyle & Yoon, 2011). These activities will help teachers build close relationships with high social-status individuals (i.e., teachers with effective experience or resources) and allow teachers to perceive higher-order support for overcoming barriers to reduce those barriers.

6. Implications and limitations

The findings have implications for the theory and practice of STEM-teacher education programs in integrating AR. Teachers share knowledge and increase their social capital in the community by developing trust, consulting research, and exchanging research information (Lin et al., 2016; Luo et al., 2020). They perceive high-level barriers by interacting with high social-status individuals. This study enriches our theoretical understanding of the teacher learning community for AR-integrated STEM education by clarifying the roles of teachers. Specifically, besides the teachers' role as a bridge to connect different networks of people in the existing AR-integrated STEM teaching community network, this study highlighted the roles of teachers as a broker to connect different groups of teachers in the trust network, a leader to guide other teachers in their AR-integrated STEM teaching community existing networks, and the teachers who are central in their trust networks, which is important for further enhancing teachers' professional development. Teachers' professional development for STEM education should pay more attention to teachers' roles in AR-integrated STEM teaching communities, and it would be beneficial for teachers to address the perceived support for overcoming barriers in a targeted manner.

These findings are aligned with the sociocultural learning theory suggest reciprocal learning, collaborating with different people/roles (e.g., experts, mentors, peers), teaching each other, and learning from one another. In this study, STEM teachers with different teaching backgrounds and technical knowledge have various roles in the community, and their learning occurs in socially and culturally shaped contexts. A positive learning community needs to encourage teachers to interact with each other and engage in informal/spontaneous knowledge construction (e.g., technical skills) and formal/research learning (e.g., ideas for stem teaching). In other words, the teacher learning community for AR-integrated STEM teaching naturally sits in the sociocultural learning theory. The findings of this study further contribute to this theory by adding an interdisciplinary learning dimension.

Based on the findings from the SNA, content analysis, and multiple regression analysis, a teachers' professional development framework should be developed, in particular for AR-STEM teaching. Thus, the study's implications involve how to build up role setting and support perception in teacher learning communities for sustainable AR-integrated STEM education.

Given these findings, this study strengthens the professional development framework for AR-integrated STEM teaching regarding social networks to fill the research gap of little discussion on AR-integrated STEM teaching from the views of teachers' perceived barriers, as well as the relationships between teachers' roles and their perceived support for overcoming barriers to AR-integrated STEM teaching. In this paper, we propose a five-dimension professional development framework for AR-integrated STEM teaching related to the teacher roles and perceived support. The five dimensions are: (1) goal guidance, (2) cultivating self-organization, (3) data-driven education equity, (4) multi-level AR-integration motivation, and (5) sustainable development, see the followings.

First, the results suggest that teachers with a high value of LTNSH play the role of a broker in the network, sharing a common AR-STEM teaching goal with other teachers. A shared value of the aim of the practice is one of the characteristics of a successful community of practice in STEM education (Jho et al., 2016). When teaching community members to have common goals, members will be more confident in their ability to recover from difficulties with instrumental help or emotional support in a shared context. Therefore, teachers with different roles in their learning community should have a common goal. Second, this study revealed that when teachers have larger values of DC, they can be viewed as potential leaders and facilitators in the trust relationships, consultant relationships, and exchange informational relationships in the community. While teachers have larger values of SH and LTNSH, they play a broker role and share resources and knowledge in different and trusted networks. These three relationships in the organization help teachers get enough support. Self-organization should be encouraged to promote the development of various collaborative self-organizations to help teachers perceive adequate support corresponding to their different roles for overcoming lower-to higher-order barriers. Third, the findings of this study indicate that the peripheral teachers (Nodes 1, 3, 7, and 21) in the community were enabled to have more teaching resources and get support for overcoming different kinds of barriers by collaborating with central teachers in the community, which is beneficial for both teacher development and education equity. Therefore, education administrators should build an interdisciplinary and intercultural community of practice with participants (such as teaching and research staff, experts, and rural teachers), provide useful teaching data resources, and help rural teachers develop knowledge and skills to promote data-driven education equity. Fourth, our work has led us to conclude that teachers are motivated on multiple levels, and the support they receive enables them to have the continuous intention to promote AR-integrated STEM teaching. It is suggested that multiple incentive strategies and support should be used to improve the AR-integrated STEM teaching community by having members play different roles. On one hand, teacher educators can show teachers excellent AR-integrated STEM teaching cases, such as using AR technology to help students understand situations and things and to stimulate students' in-depth cognition. On the other hand, school administrators should encourage teachers to participate in the teaching community and share their practice or barriers, improve teachers' self-efficacy and confidence in teaching, and help other teachers in other ways. Fifth, as a result of their strong relationships and mutual sharing of resources and ideas, teachers playing different roles within the community perceive support for their efforts to overcome the barriers of AR-integrated STEM teaching. Over time, they collaborate to create a sustainable pathway for teacher development, which is crucial for promoting AR-integrated STEM education. To enable sustainable teacher development, mechanisms and standardized management should be improved to benefit the AR-integrated STEM teaching community. For example, it would allow teachers and educators to meet or interact regularly. They will quickly establish a community culture and enhance opportunities for the professional development of the participants with collaboration between members (Erickson et al., 2005; Rehm et al., 2021).

Several limitations existed in this study. First, the AR-integrated STEM teaching community data used in the study were mainly collected from the questionnaire and interviews, while there was a lack of data on teacher interactions on the system. We could have paid more attention to data sources recorded by the system, such as text messages, voice messages, teaching video clips, and written materials. Thus, the relationship between teachers' roles and perceived support for overcoming barriers can be further evidenced by these data. Second, we suggest that teacher educators conduct targeted training for teachers by referring to teachers' roles in the AR-integrated STEM teaching community, and a special evaluation system should be established to test whether teachers' barriers have been resolved. Finally, although the study proposes strategies to promote teachers' professional development, it fails to provide targeted support for teachers while resolving different barriers. Future research can further develop corresponding support strategies to help teachers overcome barriers to AR-integrated STEM teaching.

Funding

This research was funded by the National Natural Science Foundation of China [grant number 62007010];the National Social Science Foundation for Education "Research on Mechanisms and Policies for Developing High-quality Digital Teaching Materials" [grant number BHA230159]; and the Philosophy and Social Science Project of Guangdong Province [grant number GD20CJY39].

Ethics declarations

This retrospective chart review study involving human participants was in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The Institutional Review Board (IRB) of the South China Normal University approved this study, SCNU-JXJ-2021-009.

CRediT authorship contribution statement

Xiao-Fan Lin: Formal analysis, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Thomas K.F. Chiu:** Conceptualization, Writing – review & editing. **Shucheng Luo:** Data curation, Writing – review & editing. **Seng Yue Wong:** Investigation, Writing – original draft, Writing – review & editing. **Huijuan Hwang:** Writing – review & editing. **Sirui Hwang:** Resources, Writing – review & editing. **Wenyi Li:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Zhong-Mei Liang:** Writing – original draft. **Shiqing Peng:** Writing – review & editing. **Wenkai Lin:** Writing – review & editing.

Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article. All authors have confirmed that no partial financial support was received. There is no potential conflict of interest between the authors in this study.

Data availability

The data that has been used is confidential.

Acknowledgements

The authors express their gratitude to the anonymous reviewers and editors for their helpful comments about this paper.

References

Al-Balushi, S. M., & Al-Abdali, N. S. (2015). Using a moodle-based professional development program to train science teachers to teach for creativity and its effectiveness on their teaching practices. *Journal of Science Education and Technology, 24*(4), 461–475. https://doi.org/10.1007/s10956-014-9530-8

AlNajdi, S. M. (2022). The effectiveness of using augmented reality (AR) to enhance student performance: Using quick response (QR) codes in student textbooks in the Saudi education system. *Educational Technology Research & Development*. https://doi.org/10.1007/s11423-022-10100-4

Altmeyer, K., Kapp, S., Thees, M., Malone, S., Kuhn, J., & Brünken, R. (2020). The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses-Theoretical background and empirical results. *British Journal of Educational Technology, 51*(3), 611–628. https://doi.org/10.1016/j.compedu.2019.103647

Anspal, T., Leijen, A., & Lofstrom, E. (2019). Tensions and the teacher's role in student teacher identity development in primary and subject teacher curricula. *Scandinavian Journal of Educational Research, 63*(5), 679–695. https://doi.org/10.1080/00313831.2017.1420688

Arici, F., Yildirim, P., Caliklar, S., & Yilmaz, R. M. (2019). Research trends in the use of augmented reality in science education: Content and bibliometric mapping analysis. *Computers & Education, 142*, Article 103647. https://doi.org/10.1016/j.compedu.2019.103647

Baabdullah, A. M., Alsulaimani, A. A., Allamnakhrah, A., Alalwan, A. A., Dwivedi, Y. K., & Rana, N. P. (2022). Usage of augmented reality (AR) and development of e-learning outcomes: An empirical evaluation of students' e-learning experience. *Computers & Education, 177*, Article 104383. https://doi.org/10.1016/j.compedu.2021.104383

Baker-Doyle, K., & Yoon, S. (2011). Search of practitioner-based social capital: A social network analysis tool for understanding and facilitating teacher collaboration in a US-based STEM professional development program. *Professional Development in Education, 37*(1), 75–93. https://doi.org/10.1080/19415257.2010.494450

Barragán-Sánchez, R., Corujo-Vélez, M.-C., Palacios-Rodríguez, A., & Román-Graván, P. (2020). Teaching digital competence and eco-responsible use of technologies: Development and validation of a scale. *Sustainability, 12*(18), 7721. https://doi.org/10.3390/su12187721

Burt, R. S. (1992). *Structural holes: The social structure of competition*. Cambridge: Harvard University Press.

Butler, D. L., Lauscher, H. N., Jarvis-Selinger, S., & Beckingham, B. (2004). Collaboration and self-regulation in teachers' professional development-ScienceDirect. *Teaching and Teacher Education, 20*(5), 435–455. https://doi.org/10.1016/j.tate.2004.04.003

Chai, A., Le, J. P., Lee, A. S., & Lo, S. M. (2019). Applying graph theory to examine the dynamics of student discussions in small-group learning. *CBE-Life Sciences Education, 18*(2), ar29. https://doi.org/10.1187/cbe.18-11-0222

Chai, C. S., Rahmawati, Y., & Jong, S. Y. (2020). Indonesian sience, mathematics, and engineering preservice teachers' experiences in STEM-TPACK design-Based Learning. *Sustainability, 12*(21), 9050. https://doi.org/10.3390/su12219050

Chalasani, T., Ondrej, J., & Smolic, A. (2018). Egocentric gesture recognition for head-mounted AR devices. In *2018 IEEE international symposium on mixed and augmented reality adjunct (ISMAR-Adjunct)*. https://doi.org/10.1109/ISMAR-Adjunct.2018.00045, 109–114.

Chen, C.-H., Siu-Yung Jong, M., & Tsai, C.-C. (2022). A comparison of in-service teachers' conceptions of barriers to mobile technology-integrated instruction and technology-integrated instruction. *Australasian Journal of Educational Technology, 38*(2), 35–50. https://doi.org/10.14742/ajet.7299

Chiu, T. K. F., Chai, C., Williams, P. J., & Lin, T.-J. (2021). Teacher professional development on self-determination theory-based design thinking in STEM education. *Educational Technology & Society, 24*(4), 153–165. https://www.jstor.org/stable/48629252.

Daly, A. J., Liou, Y. H., & Der-Martirosian, C. (2021). A capital idea: Exploring the relationship between human and social capital and student achievement in schools. *Journal of Professional Capital and Community, 6*(1), 7–28. https://www.emerald.com/insight/2056-9548.htm.

Demir, E. K. (2021). The role of social capital for teacher professional learning and student achievement: A systematic literature review. *Educational Research Review, 33*, Article 100391. https://doi.org/10.1016/j.edurev.2021.100391

Donnelly, D., McGarr, O., & O'Reilly, J. (2011). A framework for teachers' integration of ICT into their classroom practice. *Computers & Education, 57*(2), 1469–1483. https://doi.org/10.1016/j.compedu.2011.02.014

Erickson, G., Brandes, G. M., Mitchell, I., & Mitchell, J. (2005). Collaborative teacher learning: Findings from two professional development projects. *Teaching and Teacher Education, 21*(7), 787–798. https://doi.org/10.1016/j.tate.2005.05.018

Glazer, E., & Song, H. L. (2005). Promoting technology integration through collaborative apprenticeship. *Educational Technology Research & Development, 53*(4), 57–67. https://www.jstor.org/stable/30221209.

Glogger-Frey, I., Kappich, J., Schwonke, R., Holzpfel, L., Nückles, M., & Renkl, A. (2015). Inventing motivates and prepares student teachers for computer-based learning. *Journal of Computer Assisted Learning, 31*(6), 546–561. https://doi.org/10.1111/jcal.12097

Hammack, R., & Ivey, T. (2019). Elementary teachers' perceptions of K-5 engineering education and perceived barriers to implementation. *Journal of Engineering Education, 108*(4), 503–522. https://doi.org/10.1002/jee.20289

Hughes, J. E., & Ooms, A. (2004). Content-focused technology inquiry groups: Preparing urban teachers to integrate technology to transform student learning. *Journal of Research on Technology in Education, 36*(4), 397–411. https://doi.org/10.1080/15391523.2004.10782422

Ibáez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for stem learning: A systematic review. *Computers & Education, 123*, 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

Jho, H., Hong, O., & Song, J. (2016). An analysis of STEM/STEAM teacher education in Korea with a case study of two schools from a community of practice perspective. *Eurasia Journal of Mathematics, Science and Technology Education, 12*(7), 1843–1862. https://doi.org/10.12973/eurasia.2016.1538a

Judson, E., & Lawson, A. E. (2007). What is the role of constructivist teachers within faculty communication networks? *Journal of Research in Science Teaching, 44*(3), 490–505. https://doi.org/10.1002/tea.20117

Karam, R., Straus, S. G., Byers, A., Kase, C. A., & Cefalu, M. (2018). The role of online communities of practice in promoting sociotechnical capital among science teachers. *Educational Technology Research & Development, 66*(1), 215–245. http://www.jstor.org/stable/45018625.

Kelley, T. R., Knowles, J. G., Holland, J. D., & Han, J. (2020). Increasing high school teachers self-efficacy for integrated STEM instruction through a collaborative community of practice. *International Journal of STEM Education, 7*(1), 1–13. https://doi.org/10.1186/s40594-020-00211-w

Khuyen, N., Bien, N. V., Lin, P. L., Lin, J., & Chang, C. Y. (2020). Measuring teachers' perceptions to sustain STEM education development. *Sustainability, 12*(4), 1531. https://doi.org/10.3390/su12041531

Kopcha, T. J. (2012). Teachers' perceptions of the barriers to technology integration and practices with technology under situated professional development. *Computers & Education, 59*(4), 1109–1121. https://doi.org/10.1016/j.compedu.2012.05.014

López Solé, S., Civís Zaragoza, M., & Díaz-Gibson, J. (2018). Improving interaction in teacher training programmes: The rise of the social dimension in pre-service teacher education. *Teachers and Teaching, 24*(6), 644–658. https://doi.org/10.1080/13540602.2018.1459541

Li, S. C., & Choi, T. H. (2013). Does social capital matter? A quantitative approach to examining technology infusion in schools. *Journal of Computer Assisted Learning, 30*(1), 1–16. https://doi.org/10.1111/jcal.12010

Lin, X.-F., Hu, X., Hu, Q., & Liu, Z. (2016). A social network analysis of teaching and research collaboration in a teachers' virtual learning community: A social network analysis of research collaboration. *British Journal of Educational Technology, 47*(2), 302–319. https://doi.org/10.1111/bjet.12234

Lin, X.-F., Hwang, G.-J., Wang, J., Zhou, Y., Li, W., Liu, J., & Liang, Z.-M. (2023). Effects of a contextualised reflective mechanism-based augmented reality learning model on students' scientific inquiry learning performances, behavioural patterns, and higher order thinking. *Interactive Learning Environments, 31*(10), 6931–6951. https://doi.org/10.1080/10494820.2022.2057546

Lin, X.-F., Tang, D., Shen, W., Liang, Z. M., & Tsai, C. C. (2020). Exploring the relationship between perceived technology-assisted teacher support and technology-embedded scientific inquiry: The mediation effect of hardiness. *International Journal of Science Education, 42*(3), 1225–1252. https://doi.org/10.1080/09500693.2020.1755475

Lo, J.-H., Lai, Y.-F., & Hsu, T.-L. (2021). The study of AR-based learning for natural science inquiry activities in Taiwan's elementary school from the perspective of sustainable development. *Sustainability, 13*(11), 6283. https://doi.org/10.3390/su13116283

Luo, T., Freeman, C., & Stefaniak, J. (2020). "Like, comment, and share"-professional development through social media in higher education: A systematic review. *Educational Technology Research & Development, 68*, 1659–1683. https://doi.org/10.1007/s11423-020-09790-5

Ma, S., West, M., Herman, G. L., Tomkin, J., & Mestre, J. (2016). Studying faculty Communities of Practice through social network analysis. In *2016 IEEE frontiers in education conference*. IEEE. https://doi.org/10.1109/FIE.2016.7757561.

Margot, K. C., & Kettler, T. (2019). Teachers' perception of stem integration and education: A systematic literature review. *International Journal of STEM Education, 6*(2), 1–16. https://doi.org/10.1186/s40594-018-0151-2

Mehra, A., Kilduff, M., & Brass, D. J. (2001). The social networks of high and low self-monitors: Implications for workplace performance. *Administrative Science Quarterly, 46*(1), 121–146. https://doi.org/10.2307/2667127

Milaković, M., Alfarano, S., & Lux, T. (2008). *The small core of the German corporate board network (No. 1446)*. Kiel Working Paper. http://hdl.handle.net/10419/24841.

Neal, J. W., Neal, Z. P., Atkins, M. S., Henry, D. B., & Frazier, S. L. (2011). Channels of change: Contrasting network mechanisms in the use of interventions. *American Journal of Community Psychology, 47*(3–4), 277–286. https://doi.org/10.1007/s10464-010-9403-0

Nguyen, T., Nguyen, T. H., & Tran, T. K. (2020). STEM education in secondary schools: Teachers' perspective towards sustainable development. *Sustainability, 12*(21), 8865. https://doi.org/10.3390/su12218865

Peeters, W., & Pretorius, M. (2020). Facebook or fail-book: Exploring "community" in a virtual community of practice. *ReCALL, 32*(3), 291–306. https://doi.org/10.1017/S0958344020000099

Penuel, W. R., Riel, M., Krause, A. E., & Frank, K. A. (2009). Analyzing teachers' professional interactions in a school as social capital: A social network approach. *Teachers College Record, 111*(1), 124–163. https://doi.org/10.1111/bjet.13099

Polizzi, S. J., Head, M., Barrett-Williams, D., Ellis, J., Roehrig, G. H., & Rushton, G. T. (2018). The use of teacher leader roles in an online induction support system. *Teaching and Teacher Education, 75*, 174–186. https://doi.org/10.1016/j.tate.2018.06.010

Polizzi, S. J., Ofem, B., Coyle, W., Lundquist, K., & Rushton, G. T. (2019). The use of visual network scales in teacher leader development. *Teaching and Teacher Education, 83*, 42–53. https://doi.org/10.1016/j.tate.2019.03.018

Preece, J., & Shneiderman, B. (2009). The reader-to-leader framework: Motivating technology-mediated social participation. *AIS Transactions on Human-Computer Interaction, 1*(1), 13–32. https://doi.org/10.17705/1thci.00005

Rehm, M., Moukarzel, S., Daly, A. J., & Fresno, M. D. (2021). Exploring online social networks of school leaders in times of COVID-19. *British Journal of Educational Technology, 52*(4), 1414–1433. https://doi.org/10.1111/bjet.13099

Rodríguez-Abad, C., Fernández-de-la-Iglesia, J.-C., Martínez-Santos, A.-E., & Rodríguez-González, R. (2021). A systematic review of augmented reality in health sciences: A guide to decision-making in higher education. *International Journal of Environmental Research and Public Health, 18*(8), 4262. https://doi.org/10.3390/ijerph18084262

Rozewski, P., Jankowski, J., Brodka, P., & Michalski, R. (2015). Knowledge workers collaborative learning behavior modeling in an organizational social network. *Computers in Human Behavior, 51*, 1248–1260. https://doi.org/10.1016/j.chb.2014.12.014

Sırakaya, M., & Alsancak Sırakaya, D. (2022). Augmented reality in stem education: A systematic review. *Interactive Learning Environments, 30*(8). https://doi.org/10.1080/10494820.2020.1722713

Shiau, S. J. H., Huang, C.-Y., Yang, C.-L., & Juang, J.-N. (2018). A derivation of factors influencing the innovation diffusion of the OpenStreetMap in STEM education. *Sustainability, 10*(10), 3447. https://doi.org/10.3390/su10103447

Strijbos, J. W., & Laat, M. F. D. (2010). Developing the role concept for computer-supported collaborative learning: An explorative synthesis. *Computers in Human Behavior, 26*(4), 495–505. https://doi.org/10.1016/j.chb.2009.08.014

Takeuchi, M. A., Sengupta, P., Shanahan, M.-C., Adams, J. D., & Hachem, M. (2020). Transdisciplinarity in stem education: A critical review. *Studies in Science Education, 56*(2), 213–253. https://doi.org/10.1080/03057267.2020.1755802

Toikka, T., & Tarnanen, M. (2022). Understanding teachers' mental models of collaboration to enhance the learning community. *Educational Studies, 1–18*. https://doi.org/10.1080/03055698.2022.2052809

Urválková, E. S., & Surynková, P. (2021). Sustainable development indicators-untapped tools for sustainability and STEM education: An analysis of a popular Czech educational website. *Sustainability, 14*(1), 121. https://doi.org/10.3390/su14010121

Vossen, T. E., Henze, I., De Vries, M. J., & Van Driel, J. H. (2020). Finding the connection between research and design: The knowledge development of STEM teachers in a professional learning community. *International Journal of Technology and Design Education, 30*, 295–320. https://doi.org/10.1007/s10798-019-09507-7

Vygotsky, L. S. (1986). *Thought and language* (A. Kozulin, trans.)).

Wahono, B., & Chang, C. Y. (2019). Assessing teacher's attitude, knowledge, and application (AKA) on STEM: An effort to foster the sustainable development of STEM education. *Sustainability, 11*(4), 11–18. https://doi.org/10.3390/su11040950

Wenger, E., McDermott, R., & Snyder, W. (2002). *Cultivating communities of practice: A guide to managing knowledge*. Harvard Business School Press.

Woodland, R. H., Douglas, J., & Matuszczak, D. (2021). Assessing organizational capacity for diffusion: A school-based social network analysis case study. *Evaluation and Program Planning, 89*, Article 101995. https://doi.org/10.1016/j.evalprogplan.2021.101995

Yondler, Y., & Blau, I. (2023). What is the degree of teacher centrality in optimal teaching of digital literacy in a technology-enhanced environment? Typology of teacher prototypes. *Journal of Research on Technology in Education*, 1–22. https://doi.org/10.1080/15391523.2021.1950084

Yoon, S. A., Miller, K., Richman, T., Wendel, D., Schoenfeld, I., Anderson, E., & Shim, J. (2020). Encouraging collaboration and building community in online asynchronous professional development: Designing for social capital. *International Journal of Computer-Supported Collaborative Learning, 15*(3), 351–371. https://doi.org/10.1007/s11412-020-09326-2

Zhang, J., Yuan, R., & Shao, X. (2022). Investigating teacher learning in professional learning communities in China: A comparison of two primary schools in shanghai. *Teaching and Teacher Education, 118*, Article 103839. https://doi.org/10.1016/j.tate.2022.103839

Zweig, K. A., & Zweig, K. A. (2016). Graph theory, social network analysis, and network science. *Network analysis literacy: A practical approach to the analysis of networks*, 23–55.