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The central position of education in knowledge mobilization: insights from network analyses of spatial reasoning research across disciplines

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Abstract
Knowledge mobilization is becoming increasingly important for research collaborations, but few methodologies support increased knowledge sharing. This study provides insights, using a reflective narrative, into a transdisciplinary knowledge-sharing investigation of the connectivity of educational research to that of other disciplines. As an exemplar for educational research, the study evaluated the use of spatial search terms from mathematics education using: 1) an initial descriptive statistical analysis combined with bi modal network analysis of highly cited articles; and, 2) a second more comprehensive unimodal analysis using bibliographic coupling networks. This iterative analytical process provided a major if surprising insight—although Education is not particularly well connected bidirectionally to many subject areas, it appears to act as a distribution centre for knowledge mobilization, providing a central hub for gathering and analysing knowledge from across disciplines in order to generate the complex system of information that underpins society.

Keywords Educational research hubs · Social network analysis · Transdisciplinary studies · Spatial reasoning · Mathematics education

Introduction

Knowledge mobilization strategies are becoming increasingly sought after in providing a research knowledge synthesis that supports and sustains an innovative, resilient, and diverse society in a multitude of contexts (Fenwick and Farrell 2012; Naidorf 2014). Effective knowledge mobilization is an emergent process, arising from the interactions within

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research collaborations, that serves to make knowledge ready for service or action rather than slowly diffusing through traditional dissemination processes (Naidorf 2014; SSHRC 2009). The concept of knowledge mobilization embraces, or has synergy with, a number of similar or underlying concepts, including knowledge transfer, knowledge exchange, knowledge diffusion, and knowledge translation (Graham et al. 2006), but in simple terms describes knowledge sharing, how knowledge moves within and beyond a community of peers (Nguyen et al. 2017).

Despite the growing interest in knowledge mobilization, in practice it remains complex and uncertain, while the roles of knowledge mobilizers are becoming much more diverse and demanding (Powell et al. 2018). Levin (2011, p. 15) encapsulates this imperative:

> All over the world governments, universities, school systems and various other parties are looking at new ways to find, share, understand and apply the knowledge emerging from research, leading to increasing conceptual and empirical work to understand how this can be done.

A major issue affecting the uptake of knowledge mobilization processes is the lack of methodologies that can support such processes across multiple disciplines that are working on the same, complementary, and/or parallel areas of research, or that increase sharing among researchers in different fields and parts of the world (Cooper et al. 2011).

Transdisciplinary studies have been suggested as an authentic way to establish research crosstalk and resulting reciprocal influences among research disciplines (Bruce et al. 2017; Choi and Pak 2006, 2008), but such studies are rare. In a recent research review, for example, Bruer (2016) provides evidence that there are only a few collaborative studies that link research in Education[1] with that in other disciplines. This may be explained by the relative inexperience of many educational researchers in establishing collaborative relationships that are genuinely transdisciplinary—that is, holistic, problem-rooted inquiries that seek to integrate diverse expertise from across domains—rather than multidisciplinary, primarily concerned with similar themes, developed in parallel ways, but with little cross-disciplinary influence (Bruce et al. 2017; Bernstein 2015).

This article takes the form of a reflective narrative that examines the collaborative experiences of the Spatial Reasoning Study Group (SRSG), first gathered in 2012, showing how transdisciplinary research approaches are necessary if progress is to be made on important, complex problems in the mobilization of knowledge, in this case about the teaching and learning of mathematics. The SRSG is ideally suited to this task, with membership including multidisciplinary and multinational researchers with expertise in spatial reasoning across disciplines such as Mathematics Education, Mathematics, Psychology, Computer Science and Philosophy, as well as expertise across research areas in the physical sciences and cognitive sciences and expertise also in use of a diverse range of methodologies. This article outlines attempts in a collaborative study to draw together the group's expertise to enrich understanding of how various disciplines are interacting and not interacting in relationship to the domain of spatial reasoning. In outlining the experiences of the SRSG, however, evidence is also provided of the great potential for cross-disciplinary fertilization

[1] Because this writing is concerned with research within and communications among a number of disciplines, this article adopts the convention of capitalizing the names of those disciplines (or subject areas in Scopus) whenever there is a reference to recognized domains of inquiry. This convention is useful to distinguish between, for example, the discipline or subject area of Mathematics and the activity of learning mathematics.

and ways suggested for establishment of transdisciplinary research collaborations that may have the potential to better link the broader educational community across disciplines.

This article examines specifically the potential constraints on possibilities that ensue from domain-specific vocabularies and limited communication among disciplines (e.g., see Bruce et al. 2017; Mandell et al. 2017). The article outlines how SRSG members, as research collaborators, utilized methods to represent contemporary understandings of spatial reasoning within and across disciplines as an exemplar of educational research. Findings are used to examine whether it is reasonable to assert that Education might have important insights to offer other domains and vice versa. Although the initial focus is on considering how Mathematics Education can be enhanced by research on spatial reasoning, the research enabled a broader focus on how research in Mathematics Education can contribute to the literature and research in Education and other domains.

The article begins with an outline of the study context, including a summary of the theoretical background to the topic of spatial reasoning, its multidisciplinary instantiations and its potential in transdisciplinary studies and knowledge mobilization. A two-part research approach is then outlined, each part having its own dedicated method and findings sections. Initial investigations in Part 1 argue for a complex communication related to spatial terms within and across disciplines, with initial investigative steps based in a collective evaluation of spatial search terms, reported in terms of a bi-modal network analysis of highly cited articles in a broad (although not comprehensive) range of disciplines. Based on the findings of this initial collective exercise, Part 2 includes a second network analysis, undertaken by small groups and reported in terms of bibliographic coupling networks, a citation analysis measure, across multiple disciplines.

Following the two-part study approach, the discussion presents a collective evaluation of the findings and their implications. It outlines how transdisciplinary research may be undertaken so that knowledge mobilization is not inhibited by apparent blockages, one-way flows, and other limitations on communication flow among disciplines, or among collaborators. In other words, how researchers may better understand knowledge mobilization by examining common themes and research gaps and overlaps. The discussion presents support for the view that researchers are not without collective agency and can leverage multidimensional methods, such as network analysis, to increase their awareness of cross-disciplinary communications in apparently complex environments. In the process, researchers may be able to expand possibilities for truly transdisciplinary inquiry, obtaining a broader view of the fluency of research relations and the fluctuations of convergences and divergences across domains. The final section argues for the centrality of educational research and its potential impact in transdisciplinary studies.

Study context and theoretical background

Spatial reasoning and transdisciplinary studies

One of the main aims of the SRSG is to map out the terrain of established research on spatial reasoning and identify research needs that will bring a stronger spatial reasoning emphasis into educational research (Bruce et al. 2017; Davis et al. 2015; Sinclair and Bruce 2015). The importance of knowledge mobilization beyond a community of peers (such as the educational research community) is evident in research showing that the learning of spatial reasoning is not fixed or limited. Rather such learning is malleable and hence can be leveraged for productive gain in educational research and practice contexts (Hawes et al. 2017; Mulligan et al. 2013; Lowrie et al. 2017; Uttal et al. 2013).

Most importantly, though, the topic compels approaches that intrinsically and authentically combine research from across a number of learning areas or disciplines within a context of educational research. As an example of how this research impacts within disciplines, implementation of what we know about education and spatial reasoning in Mathematics Education is stymied due to research and policy attention to numeracy, which privileges numerical, quantitative, and linear approaches to thinking and problem solving (Mulligan 2015). Numerical approaches, for example, often value symbolic, linguistic, and alphanumerical forms of communication and reasoning, rather than spatial or other types of reasoning (Bruce et al. 2017; Mulligan and Woolcott 2015).

This impact suggested building onto the considerable expertise of the SRSG, expanding its collective knowledge of the importance of spatial reasoning as an under-utilized bridging mechanism between real-world experiences and mathematics curriculum (Bruce et al. 2017; Davis et al. 2015: Hawes et al. 2017; Mowat and Davis 2010; Mulligan et al. 2018). The intention was not to create something all encompassing, but rather to utilize in-group interactions and allow examination of methods to grow organically from the group's diverse expertise.

In early meetings together as the SRSG it became clear that individual group members operationalized spatial reasoning in various, and sometimes contradictory ways. For example, group members varied in the emphasis they placed on spatial reasoning as a verbally versus non-verbally mediated process or as an embodied versus cognitive process. Some members immediately thought of spatial reasoning as involving navigation and ultimately making sense of the external world while others saw spatial reasoning as a process that is more akin to what occurs in the 'mind's eye', involving mental imagery and mental and abstract simulations (see e.g., discussions in Davis et al. 2015).

Interestingly, it occurred to SRSG members that these same discussions and debates were reflected in the different disciplines and literatures that members were reading and from which members were receiving information. In subsequent examinations together of the spatial reasoning literature, in fact, it became apparent that the scope of literature in the multiple disciplines and use of multiple terminology was unwieldy (Bruce et al. 2017). There are numerous terms and definitions related to spatial reasoning and these differ across and even within disciplines and orientations, and both stand-alone disciplines and overlapping disciplines may have ill-defined boundaries and unknown relationship continuances.

In order to address these issues, members looked to transdisciplinary research to overcome the effect of multiple research disciplines following different knowledge pathways, hence preventing the shared or collective understandings that would enable knowledge to move beyond peer communities. Initial investigations focused on determining what set of terms are used across different disciplines and early group interactions, therefore, involved discussing the terms and definitions, and their relationship to the group's research. Obtaining and elucidating an informed consensus on the meaning of spatial reasoning is challenging, but through discussion, database searches, and examination of seminal work in the field, the following definition and examples were developed.

> Spatial reasoning (or spatial ability, spatial intelligence, or spatiality) refers to the ability to recognize and (mentally) manipulate the spatial properties of objects and the spatial relations among objects. Examples of spatial reasoning include: locating,

orienting, decomposing/recomposing, balancing, diagramming, symmetry, navigating, comparing, scaling, and visualizing (Davis et al. 2015, p. 48).

Although this definition provided a starting point for collaborative work it was insufficient in embracing the diversity that emerged through the group's investigation of the long and complex history of the spatial reasoning concept (Bruce et al. 2017; Davis et al. 2015). Given a group goal of trying to incorporate and extend the research in and from multiple disciplines into Mathematics Education research, the group looked to multidimensional analysis, using an appropriate suite of methods based around network analysis, to better understand the complex communication patterns across disciplines or subject areas related to spatial reasoning research.

The overall aim was to systematically assess the connections or lack thereof among disciplines through a lens on spatial reasoning. This article focuses on two research questions that were the basis of the group's developing transdisciplinary investigations in spatial reasoning.

(1) How can researchers determine if, and in what way, spatial reasoning research in Education draws on and connects to spatial reasoning research in other disciplines?
(2) How can the examination of the complex network of connections across disciplines, using network analysis, inform future research and expand notions of spatial reasoning in Education?

The group's developing attempts to answer these questions encouraged consideration of the broader context of Education and its relationship with other disciplines along with the outlining of potential methods for others wishing to follow similar transdisciplinary research pathways that focus on knowledge mobilization. With this in mind, the group considered how to determine if, and in what way, disciplines are talking to each other (or not) with respect to Education—developing a cross-disciplinary lexicon and foregrounding commonalities and divergences in vocabularies among disciplines. The group also considered the methodologies that could help educational researchers negotiate the complex landscape of transdisciplinary studies, applying network analysis as a research methodology for supporting knowledge synthesis across multiple disciplines. In effect the SRSG was participating in action research on itself: conducting the research and reflecting on group actions, process and impacts, co-creating collective knowledge to shape the next round of actions (e.g., see Reason and Bradbury 2001). In contrast to more conventional action research approaches, however, the group decided to also employ the additional nuancing offered by the visual and quantitative power of network maps and their representation (Borgatti and Halgin 2011).

While understanding the broader field and the interconnections between and among these fields has the potential to expand developments in spatial reasoning that have an impact on mathematics teaching and learning, and on Education more generally, the wider considerations are of interest to the broader community of educational research as they pertain to challenges to transdisciplinary research more generally (e.g., see discussion in Bernstein 2015; Choi and Pak 2006, 2008).

Knowledge mobilization and complex networks

Given that knowledge mobilization is known to be complex, the study activated within-group expertise and experience related to the theoretical frames and analytical tools that are used to examine the complex networks which researchers are known to inhabit. This activation gave rise to a consideration of network theory as fertile ground for exploration of complex networks (Mowat and Davis 2010; Woolcott et al. 2014).

Studying the underlying network structure of system has proven itself to be a useful methodology in examining complex systems, since many features of such systems arise from their basic elements and the underlying network structures, rather than specifics of the system objects and interactions (Borgatti et al. 2009). Network theory "refers to the mechanisms and processes that interact with network structures to yield certain outcomes for individuals and groups." (Borgatti and Halgin 2011, p. 1168). The theory is concerned with the examination of network variables, such as position or strength of ties (connections) in a network and influences that may act on a network structure. Network theory effectively provides a framework for interpreting the patterns of interactions within a complex system both at the level of the individual actor (be it person, place or institution), such as at the dyad (pair) level, and at broader levels that may include the entire system.

Network theory is typically applied as network analysis (sometimes called social network analysis), where the system is reduced to a set of actors (or actants) called nodes and a set of relationships called edges that link the nodes together (Borgatti and Halgin 2011; Newman 2010). Network analysis has become a powerful and well-tested methodology for representing and examining relationships in terms of system connectivity. It follows a well-established analytical method that allows qualitative mapping and quantitative analysis of the relationships between nodes connected in a network (Borgatti et al. 2009; Hanneman and Riddle 2005).

Network analysis has been applied across a number of differing disciplines, largely because the rules governing network relationships remain independent of the nature of the subjects being linked (Newman 2010). It is only recently, however, that network analysis has begun to have an impact in educational research (Brown and Poortman 2018; Carolan 2013; Daly 2010: Grunspan et al. 2014; Lund et al. 2015; Morel and Coburn 2018). Modern software developments have facilitated fast and reliable analysis of large network data sets and can provide representations both as maps and associated network metrics (Borgatti 2012). It was important in the group's research endeavors that members of the SRSG had demonstrated expertise in using such network software in recent Mathematics Education studies (Bruce et al. 2017; Woolcott et al. 2015).

Research approach

The research adopted a sophisticated mixed methods approach that, while drawing on bibliometric data, engaged a collective process of large and small group reflective practice, where SRSG members brought together their own knowledge, skills and experiences, including theoretical perspectives and established practices. The dynamic feed forward and feedback interactions between large and small groups of members, in combination with network analysis, allowed a closer, more nuanced examination of significant stages in an iterated exploration of spatial reasoning and its implications for knowledge mobilization.

The initial analysis (Part 1 below), drew on established descriptive statistical along with network analytical methods, some of which the SRSG had used previously, to determine how Education draws on and connects to spatial research in other disciplines (Bruce et al. 2017). Based on findings from Part 1, the second analysis (Part 2 below) examined how network analysis, in a context of transdisciplinary studies, could be used to explicate the role of studies in Education in knowledge mobilization across disciplines.

Part 1: the initial investigation

Data and methods

An initial listing of eleven key spatial terms used across disciplines was generated based on the SRSG's previous work on a spatial reasoning knowledge timeline, tracing its development within and across disciplines throughout recent history (Bruce et al. 2017 p. 147). In order to manage the scope of the literature review and potential network construction, a modified Delphi technique (Green et al. 2007; Rowe and Wright 1999) was used to obtain a consensus of the top six terms. (Process detailed in the "Appendix") This Delphi process made the database manageable while, at the same time, provided content validity, giving rise to the terms: spatial visualization; spatial reasoning; spatial ability; visual thinking; mental imagery; and, spatial sense.

A search was then conducted using the research database Scopus, considered one of the most comprehensive research databases currently available (Jacsó 2011; Leydesdorff et al. 2016). Scopus includes a broader range of journals and disciplines compared to other databases such as, ProQuest, ERIC, and Google Scholar (Aguillo 2012; Bosman et al. 2006). As well, Scopus also allows for searches to be completed by subject areas, with a total of 27 subject areas.[2] The search process allowed for identification of the ten most-cited or Modal Scopus Subject Areas that used this spatial term and, from this, the 10 most cited papers in each of these subject areas. (Detailed in the "Appendix")

Using these data, and the related citation data, a spreadsheet of counts by subject area as to how each cites other subject areas was generated manually for each of the key spatial search terms. From this data matrix, the team created a heat map of occurrences (Fig. 1), which illustrates the concentration of the subject areas by the frequency of their citation rates (both within and across subject areas). Based on this initial mapping, a process was developed for identifying significant publications in modal subject areas (and, therefore, in many cases disciplines) that included a selection of spatial reasoning terms in order to determine what a network of research on spatial reasoning might look like. This process involved determining key words for searches, selecting a database for searching, developing a search process, conducting the searches, loading the search counts into a large data base, and generating representations that illustrated the data.

An end result of this process was the first network analysis, with construction of a bimodal (2-mode or 2-partite) network following Woolcott et al. (2014). Matrix data were subjected to a process of software-based analysis in UCINET *v6.509* (Analytic

[2] All journals within the Scopus database were classified in one or more subject areas (totaling 27 at time of analysis). Neuroscience, Mathematics, and Psychology are each considered major subject areas, which may (or may not) correspond to disciplines. Mathematics Education journals are typically classified under either the subject areas of Mathematics or Social Sciences.

	Psychology	Social Sciences: Non-education	Social Science: Education	Medicine	Neuroscience	Arts and Humanities	Biochemistry, Genetics and Molecular Biology	Computer Science	Engineering	Agricultural and Biological Sciences	Mathematics	Pharmacology, Toxicology and Pharmaceutics	Business, Management and Accounting	Dentistry	Earth and Planetary Science	Decision Sciences	Economics, Econometrics and Finance	Environmental Science	Health Professions	Chemical Engineering	Immunology and Microbiology	Nursing	Chemistry	Physics and Astronomy	Material Sciences	Energy
SR-Psychology	1399	321	12	1389	1172	303	183	110	9	104	8	1	31	0	0	0	35	18	41	0	0	18	0	0	0	0
SR-Neuroscience	658	101	20	536	700	112	163	58	4	75	6	22	2	3	0	0	0	0	38	0	0	0	0	0	1	0
SR-Education	125	47	243	8	7	15	7	45	64	2	21	0	4	0	9	0	0	1	0	16	0	0	45	0	0	0
SR-Environmental Science	5	101	0	3	0	8	11	53	13	78	17	0	7	0	49	35	4	139	0	1	0	0	1	0	0	3
SR-Medicine	381	46	7	851	280	97	186	3	2	4	0	36	0	0	0	0	0	0	90	0	1	0	1	1	0	0
SR-Arts and Humanities	11	25	14	12	0	10	4	36	10	3	14	0	4	0	6	2	0	0	0	1	0	0	0	0	0	0
SR-Social Sciences	7	163	1	9	3	8	2	42	18	1	5	0	111	0	5	2	8	42	0	2	0	0	0	0	0	0
SR-Agricultural and Biological Sciences	20	2	3	9	18	2	46	4	7	150	1	1	0	0	14	3	0	28	0	2	20	1	0	0	0	0
SR-Computer Science	80	35	5	84	44	21	22	337	227	0	82	0	2	0	9	2	0	7	24	0	0	0	0	1	0	0
SR-Engineering	2	9	9	0	0	5	0	36	110	1	11	0	6	0	1	1	0	3	0	0	0	0	0	3	1	19
SR-Biochemistry, Genetics and Molecular Biology	87	8	0	157	98	6	88	8	2	7	0	10	0	0	0	0	0	0	0	0	0	8	6	0	0	0
SR-Pharmacology, Toxicology and Pharmaceutics	41	11	0	111	53	3	5	0	0	0	0	52	0	0	0	0	0	0	1	0	0	5	0	0	0	0
SR-Earth and Planetary Science	49	54	5	10	10	0	0	29	9	2	14	0	8	0	75	1	0	12	0	0	0	0	0	30	1	1
SR-Physics and Astronomy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	1	0	0	0	0	0	1	0	0
SR-Business	24	17	1	3	0	10	0	7	3	0	0	0	63	0	0	6	43	0	0	0	0	0	0	0	0	0
SR-Nursing	3	0	0	59	5	0	1	0	0	1	0	3	0	4	0	0	0	0	3	0	1	33	0	0	0	0

Fig. 1 A heat map of the disciplines generated from the citations derived from the six spatial reasoning terms. The map summarizes the initial spatial reasoning search process, with darker shades indicate more activity and lighter shades indicate less activity. The subject area doing the citing is indicated by the prefix SR (left-hand column). Articles being cited (the source papers) are from the subject areas listed in the top row

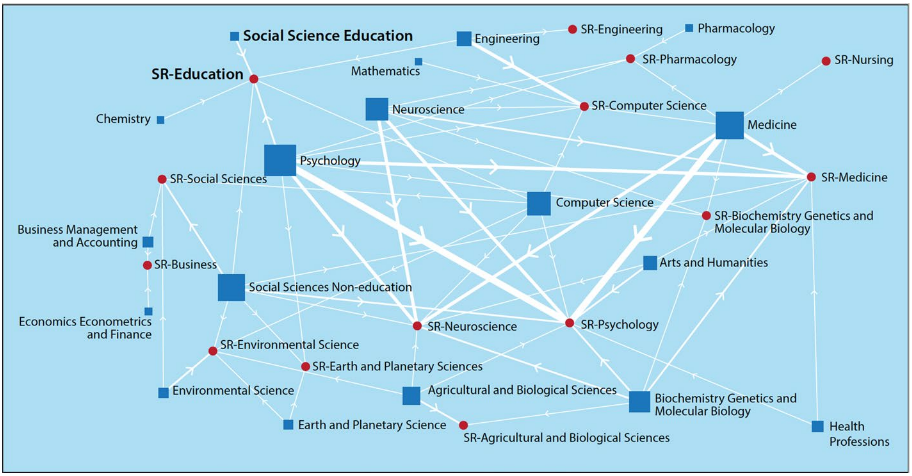

Fig. 2 A bimodal network map representing the number and direction of citation connections between subject areas (and the Education sub-group). The circles (of uniform size) represent the subject areas doing the citing (indicated by the prefix SR standing for spatial reasoning). The squares represent by size the number of papers from differing subject areas that were cited (the source papers). Heavier weighted arrows (edges) show larger numbers of connections (greater than 25 in this case)

Technologies) to produce a suite of graphical representations, weighted by degree (number of nodal connections). This analysis provided a visual overview or snapshot of the structure of the interconnectivity of terms by subject areas, with nodes (circles and squares) connected by lines (edges), such as illustrated in Fig. 2. This was not by any means a conventional citation analysis, but rather a selective process that associated a spatial terms search across subject areas with an associated citation search in key papers in those subject areas, in line with the more intricate multidimensional analytical processes used to produce networks of relationships in Biancani and McFarland (2013) and Calma and Davies (2015).

Findings from the initial analysis: education as a 'silo'

The heat map generated in the initial analysis (Fig. 1) makes obvious several important connections in scholarly publications across subject areas and Education (a sub-category of the subject area, Social Sciences) as they relate to spatial reasoning.

The map illustrates the argument presented in previous work from the SRSG (Bruce et al. 2017) that there has been both a convergence and divergence of information mobilization among disciplines since the internet revolution. Firstly, statistical analysis of the matrix data illustrates that citations tend to be grouped within subject areas. For example, for Medicine (left-side column, with the SR designation standing for spatial reasoning), a total of 1986 citations were found that used the six spatial reasoning terms. Of these, 851 of these were within Medicine (42.8% of all citations). Similarly, in SR-Engineering, 110 of the 217 citations were within Engineering (50.6%) and in SR-Education, 243 of the 661 citations were within Social Sciences-Education (36.9%). The lowest rate of citations within subject areas was Earth and Planetary Sciences (24.2%), with the highest being Physics and Astronomy (90.5%). Such insularity helps to make sense of the lack of a coherent vocabulary across domains, with similar terms being used in very different ways (e.g., *visualization* is sometimes treated as an element of spatial reasoning and sometimes treated as a near-synonym) and somewhat different terms being used interchangeably (e.g., *reasoning*, *ability*, *awareness*, and *sense*).

Secondly, the subject areas tend to be clustered with respect to the spatial reasoning search terms used here. Some sets of terms, for example, appear most often in Medicine and Neuroscience. In addition to modest education warm spots (e.g., mid-range shades), the subject areas related to studies in human sciences, such as Psychology, Medicine, and Neuroscience, along with Environmental Sciences and Engineering show a particular concentration of spatial reasoning activity (mid-range to darker shades). A strong argument can be made that such a concentration is centered on the STEM disciplines, although Physics and Astronomy are not featured as strongly.

The network representation (map) in Fig. 2 shows the results of our initial bimodal analysis of the connectivity of the discipline of Education to subject areas in Scopus. The directed network map illustrated was one of a suite of maps generated using weighted connections (edges) in the initial analysis, in this case weightings that eliminated connections comprising less than 25 edges. The squares in Fig. 2 represent the subject areas of the source papers, with the size of the square depicting the relative (total) number of cited papers from each subject area (with larger squares positioned more centrally in the network). The circles (of uniform size) represent the subject areas doing the citing (indicated by the prefix SR standing for spatial reasoning).

This directed network offers the advantage of showing, via the thickness and direction of the arrows, the extent to which the source papers in a particular subject area are being cited by papers in the SR subject areas (those doing the citing). For example, the arrow into the SR-Education discipline (circle, top left) indicates that articles in this node have cited more articles in the subject areas of Psychology (large square below right) than in Engineering or Chemistry (smaller squares, top right and left).

Figure 2 serves to highlight that there are a significant number of situations where information flow along a pathway between pairs of subject areas (from squares to circles) may be poor or non-existent—that is, there may be roadblocks or gaps instantiated as missing or small numbers of connections (edges). For example, there is no connection on this diagram, in either direction, between Mathematics and Education, or between Neuroscience and Education. By way of contrast, there are strong connections (and limited roadblocks and gaps) with respect to spatial reasoning between some subject areas, with the largest cross-connectivity among Psychology, Neuroscience and Medicine.

Further limitations in the flow of knowledge across this network can be seen in Fig. 2, for example, where SR-Education (circle) is citing a number of subject areas (squares), such as Engineering, Psychology and Computer Science, but that many of these subject areas (in this case they are also disciplines) are not citing Education. Although SR-Education is citing research in Psychology, this is a one-way flow with much less research from Education being cited in SR-Psychology. The diagram supports the results of the statistical analysis of the matrix (in the Fig. 1 heat map) indicating that Education is not particularly well-connected to many subject areas (apart from the Social Sciences) and implies that Education is borrowing richly from other disciplines, but that this is one-way, with other disciplines not citing Education in any substantial way with regard to spatial reasoning.

The suite of illustrations produced by this analysis, including Fig. 2, suggest opportunities for creation of mobilization linkages between strongly connected disciplines and Education. Nuanced examinations of such themes are developed in Davis and the Spatial Reasoning Study Group (2015), where four cases were explored in which communication gaps between mathematics education and research in other disciplines highlight distinct issues involving such matters as diverse disciplinary intentions, divergent vocabularies, and systemic isolations.

The emerging suite of networks also held many surprises. For example, the extent to which spatial reasoning has been studied within Medicine and the physical sciences is substantive and includes extensive application in tertiary education (particularly in health and engineering professions), although these literatures and practices are isolated from most educational research. A similar finding was reported by Lund et al. (2015) in relation to a scientometric analysis of global education research from 200 to 2004, as well as by others in relation to connections between educational research and that of other disciplines (e.g., between Cognitive Science, Border field literature and Education, see discussion in Youtie et al. 2017). These findings together suggest that Education researchers may benefit from engaging in two-way interactions with these research areas in order to promote knowledge transfers and exchanges as part of a broader mobilization process. The current analysis delineated the view that one of the reasons for limited communication to and from Education may be the lack of a unified vocabulary, with similar terms being used in very different ways and somewhat different terms being used interchangeably.

This initial analysis supports a view that spatial reasoning research emanating from Education, and Mathematics Education within it, does not appear to be playing as significant a role as that emanating from other disciplines, such as Psychology, in terms of knowledge mobilization or knowledge exchange. We looked, therefore, to a second analysis for further methodological resolution of the issues (raised in the introduction) related to increase sharing of research knowledge among diverse researchers.

Part 2: the second follow-on investigation

It became increasingly apparent as the research progressed in these analyses that beginning with face-to-face discussion facilitates exchange and consolidation of information—being together as a large group assisted in immediacy of communication flow and rapid communication of ideas that involve multiple communication modes acting simultaneously. A less nuanced form of communication, but one that may result in closer exchanges, was enabled by subsequent meetings that offered the advantage of temporal delays, allowing gestation of ideas formed in the initial meeting and elaborated in small group meetings. Meeting iterations with a temporal interval allowed information to be obtained from outside the group and then brought back to the group for further consolidation and emergence—they also permitted validation of innovation that developed within the group and allowed a stronger collaboration of other connected collaborations to develop—as reported by all members of the SRSG.

While these types of iterated interactions offer inbuilt redundancies—not all members have to be present all of the time—a core collaborative connectivity needs to be present and some long-term connectivity that had a face-to-face element was able to be achieved across the group. The discussion presents a collective evaluation of the findings and their implications. The large group interactions enabled rich discussions around anchor points (system boundaries) and did not necessarily have the focus on an end point that the small groups may have had (or that projects have if they are not open-ended or focused around a larger problem).

Data and methods

The network analysis process generated in Part 1 was of substantive value in identifying important research objectives and specifying methodological ways to address and understand the complexity and interconnections between and among fields of study related to spatial reasoning. There were distinct advantages in having a collective large group interaction for the initial analysis, not the least being the generation of a shared understanding of the process and findings.

There was a consensus view, however, of a need to subsequently refine the initial process and expand the number of included citations in order to provide a larger network of unimodal (1-modal or unipartite) connections. While the initial bimodal analysis offered a rich understanding of the two-way connections between disciplines, the simpler presentation of a unimodal analysis offered the advantage of viewing connections between the same type of nodes (Opsahl 2011). The second type of analysis was used, therefore, to overcome some limitations in the initial process, including: low frequency of some keywords; issues with relevance to mathematics education in some citations; lack of iteration in the search process; and, larger numbers of references in non-education disciplines relative to Education.

This second network analysis acknowledged, therefore, the limitations of the initial analysis, but built on its most successful feature, the identification of key disciplines. The second set of methods, therefore, was developed to address the following five objectives:

- identify subject area-specific keywords and areas of research using an iterative citation search and documentation approach;

- ensure all subject areas are represented by using the expanded keyword search to generate a substantially larger set of citations (up to 200,000 citations);
- use bibliographic coupling to identify highly influential documents and authors within and across subject areas within this database;
- generate a citation network to help visualize influential journals and research within various disciplines; and,
- determine what documents and which authors educational researchers cite, and not cite, in relation to spatial reasoning.

This expanded search included tools, techniques, tasks, and research fields that require the application of and/or study of spatial reasoning in order to attend to research within specific disciplines that might otherwise go unrecognized in studies that targeted mathematics and spatial reasoning. For example, the following words are relevant to spatial reasoning within different disciplines, but may not have been identified within the initial focus on mathematics education: spatial cognition; spatial decision making; spatial knowledge; spatial learning; qualitative spatial reasoning; 3D visualization; geovisualization; spatial navigation; spatial modeling; and, cognitive mapping. The overall process involved identifying keywords specific to subject area using an iterative search process to expand the number of search terms and number of citations reviewed.

The search again used Scopus, but to maintain a balance across subject areas approximately 1500–2000 of the most frequently cited refereed articles in each subject area were identified based on a broad range of keywords. The process comprised four iterations, with a culling of the author keywords after each search in order to maintain a list of frequently used keywords relevant to spatial reasoning and Education. (Process detailed in the "Appendix") As a final stage before a second network analysis, brief descriptions were generated for each of the 151 keywords identified as an end result of the process, determining which should be used as the basis for a citation network, generating a final set of 32 keywords and completing the co-citation analysis and network construction. A separate search was also conducted using the final 32 keywords against five mathematics journals identified within Scopus as those publishing articles related to spatial reasoning in Mathematics Education. The iterative process, and the search of Mathematics Education journals, resulted in a final dataset that included approximately 38,000 unique articles.

Unlike the bimodal analysis employed earlier, the unimodal analysis employed bibliographic coupling, a citation analysis measure, to examine citation patterns across the dataset using the journal name as the unit of analysis (Zhao and Strotmann, 2015). Two works were considered coupled if both cited the same source—the more sources the two texts have in common in their reference lists, the stronger the coupling. A distance-based citation network was produced using VOSviewer *version 1.6.6* (Van Eck and Waltman 2016) (Fig. 3a, b). The co-authorship network analysis is described and illustrated here as embracing the most strongly linked disciplines identified in the initial network analysis, disciplines that Education appears to be biasing in drawing on research literature.

Findings from the second analysis: Education as an information hub

The unimodal network is illustrated in the linked, colored clusters generated for one of a suite of network maps (Fig. 3a, b), in this case with 5 or more documents in a source and the top 500 link strengths of the bibliographic coupling with other sources (as detailed in

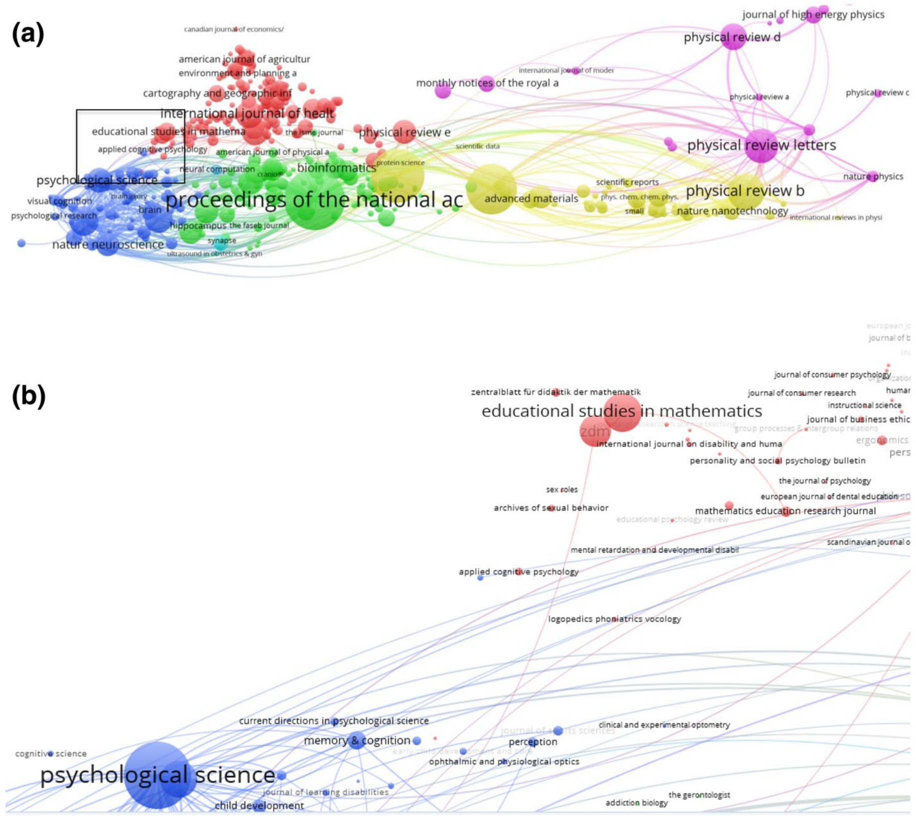

Fig. 3 **a** A mapping of spatially relevant research in the 27 Subject Areas within Scopus, with the addition of specific mathematics education journals. (date of analysis: 2018.02.08). The rectangular enclosed area is enlarged as **b**. **b** Enlargement of the rectangular enclosed area of **a**, showing the three mathematics education journals (top left in red) and the sparseness of their bibliographic connections to journals in the 27 Subject Areas

the "Appendix"). The greater the relation, the closer the journal names appear, and, the more coupled the journal is with other journals, the larger the node.

The red cluster in Fig. 3a could be considered as a 'non Natural Sciences' cluster, comprising Social Sciences and Arts and Humanities journals, including as well, Business Management, Economics and Econometrics, and Nursing and Computer Sciences. This cluster contains most of the Education journals, including three of the five Mathematics Education journals named in the search outputs, but there is little or no connection between the Mathematics Education journals and those in the other subject areas in the red cluster—their only significant connection in this network map is the link to Psychological Science in the blue cluster (see detail in Fig. 3b).

Figure 3a also shows that the green and blue clusters are well connected, comprising primarily journals in the subject areas of Psychology, Neuroscience, Medicine, and Biochemistry and Genetics. There is also a strong connection between the green and the yellow cluster, relating many of the 'hard' sciences to the health and medical sciences. The relationships among the hard sciences are also reflected in the evident connectivity between the pink (Physics and Astronomy and related disciplines) and yellow clusters. The implication for spatial reasoning is that the majority of knowledge mobilization (as indicated by the majority of connected articles) appears not to be located in Education or Mathematics Education, but in the Natural Sciences—the non-red clusters.

What is interesting here, since a unimodal citation analysis has been used, is that further analysis could determine any structural holes (i.e., breaks) in the network (Burt 2004) or weak links between nodes (Granovetter 1983) that may be analogous to the gaps and roadblocks that we have found in our initial network analysis. Such examination would provide a way of circumventing, or connecting to, the current hubs in the networks of the second analysis, which lie within the Natural Sciences. Any such further analysis would need to be examined, however, in light of any determination as to where Education should be working harder to connect with other disciplines.

Discussion

What insights are afforded that were not previously known?

The framing of the research in studies of spatial reasoning within Mathematics Education offered a fecund opportunity to exemplify the establishment of research and practice collaborations that can move Education into a more connected future through emergent knowledge mobilization processes. The discussion, therefore, considers significant issues that have arisen from this iterative style of alternate analyses and how this may provide a way forward for Education in general, and Mathematics Education in particular, that may improve connectivity through transdisciplinary approaches and clarify its role in knowledge sharing across disciplines.

The network analytics engaged allowed the group to: (a) illustrate the recent convergence and divergence of disciplines associated with spatial reasoning; (b) explore the links between the use of spatial reasoning terms in Education and database subject areas; (c) illustrate the complexities and networked nature of spatial reasoning research; and, (d) identify strong versus weak connections across identified networks. The methods that arose from the analyses provided a way to conduct a nuanced, historically situated and transdisciplinary review of the literature, as well as providing a method that builds knowledge mobilization networks by extending and overlaying both similar and different types of citation searches.

The key finding that arises from these two sets of analyses is that Education as a discipline appears to be citing the other subject areas (and by implication disciplines) examined, at least with regard to the spatial reasoning search terms used, but that this situation is reversed with regard to those other subject areas—they are not citing Education very much at all. The network analyses that the SRSG has been able to develop point to the lack of both communication and common terminology across such knowledge domains. Of particular concern is the marginal interaction of educational research with other domains needed to transcend typical disciplinary silos and to positively influence practical and theoretical activity in an integrated fashion (see also discussion in Choi and Pak 2006, 2008; Lund et al. 2015).

The selection of terms and the constraints of the disciplinary boundaries limit the conclusions that can be drawn about the nature of the research on spatial reasoning and the interaction between the subject areas and disciplines related to spatial reasoning. In taking this opportunity, however, the group has shown that iterative or repeated experiences that involve collective expertise of a collaborative research group may be effective in mobilizing the influence of educational research across disciplines (see also Lund 2016).

The SRSG would certainly be interested in whether other styles of analysis would come to a similar set of conclusions with regard to Education as a silo with regard to spatial reasoning. An expectation, however, would be that the process used, or the key terms used, should produce a similar network of relationships across disciplines, or at least a similar narrative. In other words, it is expected that analysis done using other methods should indicate the same silo effects. Other analyses are welcomed that either support this expectation—another network constructed using variations on these criteria will still be a network of relationships roughly of the same nature and relating similar things—or which provide an account of how Education may not be siloed.

Alternatively, or in addition, a network could be constructed over a different time period, for example, a pre-internet web of relationships, in order to provide a comparison with post-internet networks constructed for the 1995–2015 period[3] (provided that search criteria are similar). Such a web would serve to verify the convergent and divergent nature of the timeline provided in the earlier study (Bruce et al. 2017), and its linearity and discreteness. This type of comparison may be complemented by refinements that utilize the degree of impact of a journal and the role this may play in the search processes, particularly since educational journals have lower impact in general than science journals.

New contributions to methods of analysis of complex systems in Education: The process of the creation of evidence

What we can see from both types of network analysis is that Education seems to have missed the convergences and divergences that resulted from the internet revolution. This rigidity is reflected in curricula that do little other than direct participants through an industrial model even though this may no longer have relevance for many of the students in that system (Davis et al. 2015). Research in spatial reasoning in Mathematics Education may reflect the situation in Education more generally in that it does not seem to be making paradigm shifts that direct research in spatial reasoning or that provide convergence or divergence into new and exciting fields of discovery.

This study has illustrated, however, that there is a novel and effective method for analyzing and synthesizing existing research knowledge, conceptions, and gaps, through the application and illustration of network analysis procedures that collapse typical disciplinary bounds and allow for insights, intervention points and opportunities for further exploration of knowledge mobilization processes. The analytical approaches have included an elaboration of the importance of relationships (edges) in the network, directionality of these relationships, as well as impact and reach, details that are rarely identified between Education and other knowledge domains.

These concerns, and the documented methods of resolution, draw on knowledge mobilization as an essential activity in bridging discipline, research, practice, and policy gaps in educational research (Cooper et al. 2011; Levin 2011). The domain of spatial reasoning

[3] The internet revolution, partly through establishment of widespread individual use of hypertext and the world wide web from the mid 1990s (at least in OECD countries) sparked an increase in transdisciplinary studies globally. The year 1995 is significant as it marks the decommissioning in the USA of the National Science Foundation Network (NSFNet) and full commercialization of the Internet (Tronco 2010).

provides a particularly salient example of how a burgeoning area of knowledge and research may be disjointed. That is, Mathematics, Mathematics Education, Psychology, and other domains are not fully aware of the range of related work across domains, nor is there an integration (or synthesis) of findings and knowledge that bring together these seemingly disparate pockets of knowledge. Systematically identifying the relationships between and among the domains and disciplines related to the various conceptions of, and research on, spatial reasoning is at the heart of knowledge synthesis.

The analyses illustrated here show that the central purposes of projects conducting a complex network analysis might be to: (1) synthesize current knowledge across the disciplines; (2) identify disparities and determine exactly where the domains and disciplines are talking to one another, or not talking to one another; and, (3) create an evidence-based agenda for future work in the selected research area. The knowledge mobilization 'products' generated through this synthesis project may be multi-layered, with some typical of academic work, and others quite unique (Cooper et al. 2011). A helpful analogy on the fusion of horizons is offered in Gadamer et al. (2004), where many seemingly disparate perspectives and discipline-bounded knowledge bases can be unified in a common multi-hued, rich horizon for researchers and ultimately for educators working with students.

Is education central to knowledge mobilization?

What initially seems apparent from these analyses is that Education should be looking to other knowledge domains and disciplines (e.g., Medicine, Psychology and Neuroscience) in order to forge collaborations and working relationships that engender close ties across all disciplines engaged in those collaborations. While it may be true that such close ties may allow Education, and Mathematics Education specifically, to flourish through rich interchanges rather than rich borrowings, it is the idea of rich borrowings that became of interest in discussions at the group level—we acknowledged the cognitive bias of the group, and of the group members, and its influence on siloed research. A closer examination of the network analyses opened up the realization of an alternative view that says Education *should* be making rich borrowings—and that it may not be the primary role of educational research to engender rich interchanges.

This does not mean that the findings do not recognize the schism between the so-called Natural Sciences (which includes all of the modern biological and physical sciences) and the Social Sciences (and later the Humanities) that arose around the time of the industrial revolution and which remains apparent in modern educational research and practice (Woolcott 2013). An argument could be made, based on the heat map (Fig. 1), for example, that post-internet convergence in the last 20 years has been across the Natural Sciences (including Chemistry, Neuroscience and other physical or biological sciences), but has not engaged the Social Sciences or Humanities.

What we are recognizing, based on the interchange of ideas that the network analyses has stimulated across the SRSG, is that the role of educational research, in fact, may be to act as a central hub in knowledge mobilization, gathering and analyzing information from a range of disciplines and using this to generate the complex system of information that underpins society. Educational research, therefore, has a crucial role in developing the knowledge, skills and experiences that constitute the cultural memory of each individual in human society (culture in the sense of Tomasello 1999), enabling its transfer from one human memory to another through teaching and learning. One of the ways Education does this is by rich borrowing from other disciplines.

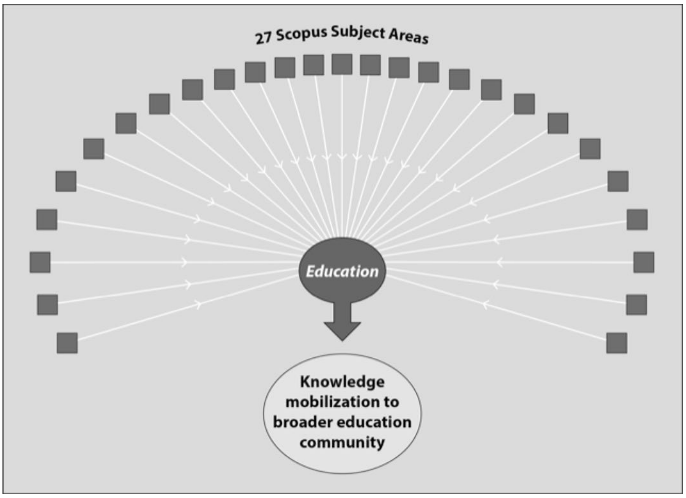

Fig. 4 An idealized interdisciplinary network with Education as the central hub

Based on an interpretation of the initial bimodal analysis in this article, Fig. 4 shows an idealized relationship network that places education as a centralized distribution center for other domains and disciplines—Education as a centralized hub for knowledge mobilization. The placement of Education as a research information hub recognizes the argument of Gura (2005, p. 1156) that Education is beset by issues related to "camps of specialists fighting to advance one theory over another" with little reference to common measurement standards or other benefits enjoyed by the Natural Sciences. A potential resolution of such issues may be to recognize that Education involves complex systems that are culturally bound and that isolating particular variables in these complex systems may not be possible (see also Lund et al. 2015; Youtie et al. 2017). A number of studies in Education have considered such systems approaches (Davis et al. 2008; Scott et al. 2017), and some of these have been applied in Mathematics Education environments (Woolcott et al. 2014; Mowat and Davis 2010). Multidimensional approaches that include network analysis, such as have been used here, may be more useful in this context than the methodologies that people use in disciplines such as Psychology, since networked approaches offer a view of complexities and nestedness within and across systems.

Such approaches may allow Education to offer a systemic view that can accommodate results from Psychology, for example, and offer alternative approaches to those currently used in disciplines such as Psychology—in other words, both disciplines may benefit if Education acts as a hub. Knowing how educational researchers negotiate the landscape of transdisciplinary research is critical and the conceptual centrality of educational research suggests that, within the Education discipline, ways need to be found that can help other domains and disciplines, rather than expecting them to help Education, an issue related to the agency of educational researchers. Further analysis is required, of course, to determine whether this centrality hub construct is useful for studies of knowledge mobilization, but the hub conceptualization suggests a framework for investigating how learning and intentionality act in applying the knowledge from research networks in a transdisciplinary way.

Conclusion

Our analyses indicate that the educational importance of spatial reasoning has been recognized in many disciplines and research domains, including Medicine, Psychology, Engineering and Mathematics. Despite the substantial volume of research into the phenomenon of spatial reasoning, however, most of it has been conducted and reported in disciplinary isolation, at least in isolation as far as Education is concerned. There appear to be deep commonalities (e.g., themes, insights), however, that might serve as reasons for and bases of a powerful, transdisciplinary research on spatial reasoning, and a more pronounced emphasis on transdisciplinary research might be timely—and perhaps even necessary—in the evolution of research in Education.

Based on the collective enterprises of the SRSG, with regard to the broader research enterprise, this article advocates an issue-specific, problem-based attitude toward inquiry—one that not only invites but compels researchers from different domains to come together around matters of shared interest. To this end, network analysis may be a method that allows interconnectivity to be considered as way to examine and establish more fluent relations in research. At the very least, such analysis might afford much expanded awareness of convergences and divergences across domains that influence and are evidence of knowledge mobilization. The network analysis completed so far has certainly had this effect, building on reviews of the past research across multiple disciplines to catalyze our research endeavors.

As part of the process of constructing a systematic overview of knowledge mobilization of spatial reasoning research, this article presents productive methods related to locating common themes and gauging research overlaps across fields. The more the group's respective interests and expertise were placed in collective dialogue, however, the more evident it became that an approach of "summing what we know" is insufficient to the complexity of the phenomena studied together. Ultimately, the analyses argue for a reconsideration of how findings from other disciplines are either ignored or translated and reduced in educational settings. The specific research interests of the SRSG also argue for an appropriate transformation of spatial findings in other research literatures into spatially and temporally effective ways of thinking across swathes of curricular content.

Appendix

Initial investigations: Delphi consensus and first network analysis

Selecting spatial search terms

The initial step in the generation of the network data was the selection of key spatial terms for use in searching for research articles with a spatial focus. In order to respond to the explosion of data from 2000 onward in the area of spatial reasoning, and to manage the size of the database, the SRSG focused on research publications since 1995 (a period approximating the time since the initial divergences and convergences of the internet revolution). An initial listing of eleven key spatial terms used across disciplines was generated based on the SRSG's work on a spatial reasoning knowledge map (Bruce et al. 2017), the SRSG's expertise across diverse disciplines, and web searches by SRSG members. These terms

Table 1 Description of steps in the fist citation search

Step 1. *Identification of 10 Modal Subject Areas*: The goal of this step was to identify the top ten Subject Areas in which most of the research was being conducted relevant to the spatial search term. This term was entered into Scopus with the search parameters restricted using the Scopus search functionality to articles or reviews (document type), publications between 1995 and 2015 (date range), and the spatial term appearing in the article, title, abstract, or keyword listing (field). The search results generated total citations by Scopus Subject Areas. From this listing, the ten *Modal Subject Areas*—those having the highest number of citations—were identified for each spatial search term
Step 2. *Identification of 10 most-cited papers by Modal Subject Area:* The 10 most-cited papers in each of the 10 Modal Subject Areas were next selected, using the "cited by" Scopus feature. The most-cited paper in each Modal Discipline was selected for a further citation search
Step 3. *Identification of the top 10 Citation Subject Areas:* Again using Scopus the reference list, each most-cited paper was used to identify the number of papers in each of the top ten Subject Areas that were cited by this most-cited paper. This number was then recorded
Step 4. *Process iteration:* The above process was repeated for each of the six spatial terms and results pooled. Consensus was obtained for 16 Modal Subject Areas that used the six spatial reasoning search terms

were: (a) geometry, (b) mental imagery, (c) spatial ability, (d) spatial memory, (e) spatial perception, (f) spatial reasoning, (g) spatial sense, (h) spatial skills, (i) spatial thinking, (j) spatial visualization, and (k) visual thinking.

To manage the scope of the literature review and potential network construction, the group used a modified Delphi technique to identify the top six terms in order to make the database manageable and, at the same time, to provide content validity. Delphi is an iterative and subjective approach used to synthesize differing expert opinion into a consensus (Green et al. 2007; Rowe and Wright 1999). Each member of the transdisciplinary group ranked independently what they considered to be the five most significant terms, providing an overall score for each term. The resulting six top ranked terms were as follows: spatial visualization; spatial reasoning; spatial ability; visual thinking; mental imagery; and, spatial sense. Aside from being the top six ranked terms overall, each of these six terms additionally appeared as the top six ranked terms by each group member.

Spatial terms citation searches

A search was conducted using the research database Scopus, which allowed for searches to be completed within one of the 27 subject areas. For each of the six spatial search terms, citation searches were completed by a pair of researchers using a three step "10–10–10" search process. The search process allowed for identification of the 10 most-cited or Modal Scopus Subject Areas that used this spatial term and, from this, the 10 most cited papers in each of these subject areas.

As outlined in Table 1, and diagrammatically in Fig. 5, the initial steps involved each of six researcher pairs entering a key spatial term in Scopus in alignment with the listed parameters.

Inter-rater reliability was determined from cross comparison of searches by each person in the researcher pair. Given the focus of the group on the discipline of Education, citations listed under the Scopus "Social Sciences" Subject Area were manually

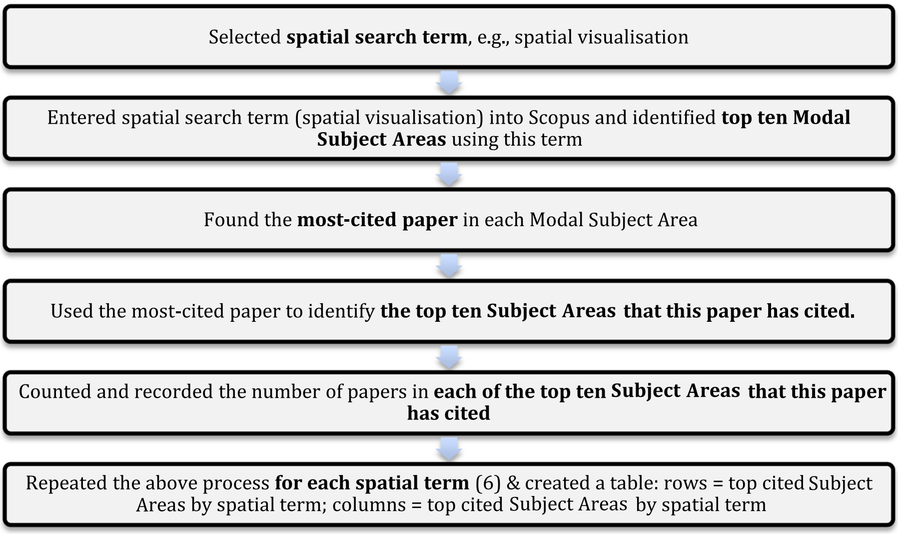

Fig. 5 The flowchart shows how each spatial search term, using the same search process, was used to find the ten most-cited or Modal Subject Areas in Scopus that used this spatial term and, from this, the most-cited paper in each of these subject areas. Using each of these most-cited papers, a list was constructed of the top ten subject areas that each of these papers was citing

reviewed and those that had authors with primary alignment in the Education discipline were coded into a distinct subject area sub-category of "Social Sciences–Education".

Using these data, and the related citation data, a spreadsheet of counts by subject area as to how they cite other subject areas was created for each of the key spatial search terms. From this data matrix, the group created a heat map of occurrences, which illustrates the concentration (darker shades meaning more activity and lighter shades indicating less activity) of the disciplines generated from the citations derived from the six spatial reasoning terms.

Small group follow-on investigations: second network analysis

Subsequent to a discussion of the limitations in the initial process, there was a realization that the following three points were significant.

- Keywords used as the basis for data collection in the initial analysis had very low frequency across all disciplines, including education, raising issues related to numbers of relevant citations.
- Based on the keywords used, the resulting citations were not necessarily relevant to spatial reasoning in the sense of Mathematics Education.
- Comparability of citations was potentially confounded by the large numbers of references in the larger disciplines, relative to Education in particular.

There was little to say that the network was specific to spatial reasoning or that we were examining educational ideas and how they are connected to other disciplines. The second

Table 2 Description of steps in the second citation search

The overall process involved *identifying keywords specific to Subject Area.* This involved an iterative search process to expand the number of search terms and number of citations reviews
Step 1. *Keyword and citation search*
In this first iteration of the citation search, all 11 of the original spatial terms identified in the initial study were used as the starting point to expand the search
Each term was entered in Scopus as a keyword search for articles for the period of 2005-present. All citations were downloaded up to a maximum of 2000 citations for each term. (Placing a maximum limit ensured that a single term did not dominate the citation results.)
The searches were merged, resulting in over 11,000 citations and a list of over 40,000 unique author keywords, complied from the cited articles in Scopus
Step 2. *The keyword list was culled using the following process*
The frequency of all keywords was calculated using a word count program after transfer to Excel
All original keywords were located as well as all known variations of the keywords (e.g., visualization/visualization)
All keywords (except those identified as original) with frequencies less than 10 were eliminated
Two researchers examined all remaining keywords independently. Words not relevant to spatial reasoning and geometry in Mathematics Education or Education were eliminated, unknown words were searched, and descriptions created, and all relevant words identified. The lists were compared, and differences were discussed. If differences remained, the term was kept in the list
Step 3. *Identification of keywords relevant to disciplines*
In the next iteration, the list of 55 keywords resulting from the above process was entered as a full set of search terms in Scopus resulting in a potential database of over 257,000 citations. In this phase, the purpose was to identify keywords relevant to each Subject Area
The 2000 most highly cited articles from each of top 27 subject areas were downloaded and citations merged. The result was a set of over 38,000 citations (since some citations overlapped disciplines) with over 66,000 unique author keywords
Step 4. *The keyword list was culled again using the same culling process as identified above*
The final keyword list included 151 words
This list is used for the basis of the preliminary results, but was reduced to a final list if 32 keywords as a more thorough description of the research related to each keyword was completed
Step 5. *An additional search for keywords in Mathematics Education journals*
This final search was conducted, with the final 32 keywords, within the five Mathematics Education Journals listed in Scopus and known to contain articles related to spatial reasoning: ZDM Mathematics Education; Educational Studies in Mathematics; Mathematics Education Research Journal; Mathematical Thinking and Learning; and, Journal of Research in Mathematics Education

process, detailed here in Table 2, was designed to overcome these limitations using a unimodal, rather than a bimodal analysis.

The second network analysis

The subsequent network analysis was based in the results of a search, again using Scopus, but using the final 32 keywords to identify refereed journal articles from 2000 to present addressing spatially relevant topics. To maintain a balance across subject areas a small working group from the SRSG identified approximately up to 2000 of the most frequently cited refereed articles in each subject area and then merged the 27 subject area citation files with the file obtained using the Mathematics Education Journal searches. The resulting dataset included approximately 38,000 unique articles uploaded using available identification of digital object identifier (doi) codes extracted from comma separated values (csv) files exported to Excel.

The unimodal analysis used bibliographic coupling analysis undertaken in VOSviewer *version 1.6.6* (Van Eck and Waltman 2016), with the journal name as the unit of analysis. The minimum number of documents selected was set at 5, and the minimum number of sources was set at 0, with the subsequent illustration based on 500 sources with the greatest total link strength. On this basis, only three Mathematics Education journals were included in the final diagram (Fig. 3a, b in the actual article): ZDM Mathematics Education, total link strength of 722; Educational Studies in Mathematics, total link strength of 423; and, Mathematics Education Research Journal, total link strength of 347.

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