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The Intellectual Structure of Metacognitive Scaffolding in Science Education: A Co-citation Network Analysis

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Abstract The issues of metacognitive scaffolding in science education (MSiSE) have become increasingly popular and important. Differing from previous content reviews, this study proposes a series of quantitative computer-based analyses by integrating document co-citation analysis, social network analysis, and exploratory factor analysis to explore the intellectual structure of the MSiSE literature (i.e. the relationships within and between subfields of MSiSE). Co-citation refers to any two articles that are jointly referenced in other articles. After the computation of co-citation analysis, 27 articles that have been co-cited at least once by follow-up studies as references were identified as the final set of core articles. The whole co-citation profile of 27 cores with the 434

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links was then visualized in a network through social network analysis, representing an overview for the intellectual structure of core MSiSE studies. The most cross-referenced underpinnings in the network focused on adaptive scaffolding for self-regulated learning to enhance students' conceptual understanding and on younger students' metacognition in online science inquiry learning environments. Furthermore, two emerging topics in the network were identified through an exploratory factor analysis as "non-technological metacognitive scaffolding media," and "behavior patterns & task analysis in technology-infused environments." Overall, the study provides an innovative review method of scholarly communication in the MSiSE literature.

Keywords Document co-citation analysis · Exploratory factor analysis · Literature review · Metacognitive scaffolding in science education (MSiSE) · Social network analysis

Introduction

Authors' citations of other people's work (intertextuality) are the foundation of and building blocks for academic writing and research that indicate the intellectual structure of a problem space. Exploration of these citations can document the established literature that serves as the empirical basis and theoretical justification for research questions, designs, procedural decisions, explanations, and supplemental support for knowledge claims. Accompanying the growing trend of the metacognition scaffolding issues in science education (MSiSE), some research reviews have attempted to analyze the content of fruitful literature and have sought to identify the direction of the future research in science education. Differing from recent content research reviews in MSiSE (Lin et al., 2012; Zohar & Barzilai, 2013), this study introduces a method of computer-based systematic analysis to explore some highly cross-referenced articles to reveal the intellectual structure and related topics for promising future inquiries.

Background

An inspection of the MSiSE research and established literature revealed some lingering issues. There appears to be lack of clarity between metacognition and self-regulated learning, several content reviews of metacognition in science education, and the potential for computer-assisted analytical procedures for conducting such reviews.

Metacognition and Self-regulation

The concepts of metacognition and self-regulated learning (SRL) in the MSiSE literature are often used interchangeably. However, previous research reports often do not share a consistent and coherent conceptualization of metacognition and SRL (Dinsmore, Alexander & Loughlin, 2008). Despite the different emphases, metacognition and SRL share a common core that involves self-awareness and regulatory actions including planning, monitoring, or evaluation (Hsu, Yen, Chang, Wang & Chen, 2015). This common core was used as the working definition to conceptualize the key terms in this present study—metacognition and self-regulated learning. Furthermore, Reiser's

(2004) idea of scaffolding has been shown to be practical in science education when it can be provided by either teachers or software tools. Combining these two working definitions, metacognitive scaffolding must reflect the following features: (1) supports provided by teachers or software tools or changes to a task made by teachers or software tools for an instructional or educational purpose, and (2) the supports or changes to the task need to intervene in learner's self-awareness or regulatory actions during science learning.

Metacognition Studies in Science Education

Research into metacognition has become a central focus in science education of the last 30 years—instructional design and classroom practices (Zohar & Dori, 2012). The use of metacognitive scaffolds has been recognized as an effective approach for helping learners self-regulate their underlying learning processes (White, Shimoda & Frederiksen, 2000), thus helping them achieve deeper comprehension and higher order thinking skills (Hattie, 2009). Recently, some science educators have proposed the idea of technology-based scaffolds to further support learners' cognitive processes when they engage in complex tasks in computer-based learning environments (Bulu & Pedersen, 2010; Kyza & Edelson, 2005; Yore, 2012). Other researchers have also found that the timing of teacher-based metacognitive scaffolding in combination with different types of computer-based procedural scaffolding have significant impacts on students' science inquiry learning (Wu & Pedersen, 2011).

Accompanying the growing trend of the metacognition scaffolding issues in science education (MSiSE), some research reviews have attempted to analyze the content of the literature and, more importantly, have sought to address the direction of the future research in science education. A research survey (Lin et al., 2012) used content analysis to examine the main features of 43 scaffolding-related empirical studies from 1995 to 2009 that were indexed in SSCI. They found that researchers preferred long-term explicit scaffolding using multiple representations to promote strategic skills and alternative assessments of learner performance. Zohar and Barzilai (2013) analyzed the content of 178 studies (2000–2012) regarding metacognition in science education. They found that conceptual understanding of science is one of the central aims of the current metacognition research and concluded that the field of metacognition in science education is in a state of growth and expansion.

Co-citation Analyses and Procedures

The field of MSiSE can be broadly divided into several subfields, such as the issues of scaffolding features (Lin et al., 2012), the metacognitive instruction, and the metacognitive aspects studied (Zohar & Barzilai, 2013). As bibliometricians have suggested, these research subfields and the literature cited by the researchers form the intellectual structure of MSiSE (McCain, 1990; White & Griffith, 1981). Its intellectual structure and evolution over time are assessed in terms of the relationships between the documents cited. The document co-citation analysis (DCA) is a computational method for analyzing the inter-relationships or the network among research documents within a research discipline according to their joint citations and thus is a valid means of exploring the intellectual structure of MSiSE research. A joint citation, or "co-citation," is defined as the frequency with which two earlier works are cited together by a later one (Small, 1973). The DCA, based on citation counts, is considered one of the representative indices for measuring the impact of a scientific article (Garfield, Sher & Torpie, 1964). The analysis of highly cited articles has become an effective way of identifying the most critical studies in current science education research.

Social network analysis (SNA) is another technique that can be used to graphically visualize and analyze the relationship and pattern of literature in the research network (Borgatti, Everette & Freeman, 2002). Integrating SNA with DCA, the co-citation network analysis becomes an effective method of visualizing the identified co-citation links into a network diagram to represent the social structure of scholarly communications. This innovative approach has been demonstrated for the visualization of contemporary computer-supported collaborative learning research (Tang, Tsai & Lin, 2014). Furthermore, exploratory factor analysis (EFA) has been suggested as a complementary means for further examining the underlying structure in a complex network (Tang & Tsai, 2015). The factorized co-citation profiles can thus provide researchers with statistical evidence to categorize the underlying patterns of MSiSE, which might reveal emerging research areas and promising avenues for future research.

Following previous co-citation studies, this study utilized three systematic and complementary methods, including document co-citation analysis (DCA), social network analysis (SNA), and exploratory factor analysis (EFA). Based on a series of analyses of longitudinal citation data, this study aims to achieve three research objectives: (1) to identify the most frequently co-cited MSiSE articles, (2) to visualize the intellectual structure of the core MSiSE studies, and (3) to highlight themes in MSiSE research. Therefore, this study is believed to be the first attempt to propose a co-citation network analysis to access the most highly co-cited ties of MSiSE research and to explore the main disseminations and trends in the MSiSE community.

Methods

This study was limited to metacognitive scaffolding in science education (MSiSE). A systematic series of quantitative methods was used, including data retrieval and selection, document co-citation analysis, social network analysis, and exploratory factor analysis to explore the intellectual structure of the MSiSE literature.

Data Selection

The high-quality research articles in MSiSE were selected from the Sciences Citation Index (SCI) and Social Sciences Citation Index (SSCI) on the Web of Science (WoS) system. A two-step screening approach for including the most representative metacognitive scaffolding research in science education was introduced.

First, a multi-keyword query was adopted to conduct the initial search of all available years in the databases. Studies with title, abstract, or keywords explicitly relating to the following features were included: (1) referring to key terms of metacognition or SRL, (2) reflecting the working definition of metacognitive scaffolding established for this study, and (3) depicting science education settings. Eight keywords used for the search included metacognit*, self-regulat*, scaffold*, prompt*, support*, aid*, cue*, and feedback*. The wildcard symbol (*) is used to enlarge the search to capture the different naming conventions of keywords in the database. The use of the keywords, metacognit* and self-regulat*, can search for articles including the terms metacognition, metacognitive, self-regulated, and self-regulation in the topic column of the WoS system. Both key terms (metacognit* or self-regulat*) used to extract targeted studies dealt with the issue concerning the blurred and divergent definitions of metacognition and SRL. An additional keyword "emotional" was used as a filter for this query to exclude studies that primarily explored factors affecting emotional problems, disorder, or emotion and behavior regulation from the child developmental perspective, since these topics were beyond the research focus. The research field was limited to three subjects listed in WoS (i.e. education and educational research, educational psychology, and educational scientific disciplines). The results of the initial search were then refined using science-learning related keywords, including physics, chemistry, biology, earth, medical, or environmental science. These steps resulted in 360 journal articles as the initial sample as of September 22, 2014.

Second, all sample articles were filtered and cross-checked by three science education researchers using five selection rules: (1) using metacognition or self-regulated learning as the theoretical or discussion base; (2) designing or introducing scaffolds for metacognitive or self-regulated learning; (3) applied in science education, i.e. physics, chemistry, biology, earth, medical, or environmental science; (4) empirical research (not review research); and (5) published in English. Only articles that met all five criteria were selected. Articles whose title, abstract, or keywords did not use at least one of the above terms but contained related terms (for example, monitoring, evaluation) were examined (full text) by two researchers to determine whether they explicitly referred to the central focus of this study. The initial results of this deliberation were verified by the third senior researcher who specializes in science education. Any discrepancies were discussed and resolved to produce consensus decisions for article selection. Studies in technology, mathematics, and computer science were not included. Furthermore, articles that did not provide intervention or scaffolding to learners (e.g. Eilam & Aharon, 2003; Grabe & Holfeld, 2014; Martin, Mintzes & Clavijo, 2000) or which dealt exclusively with conceptual or procedural scaffolding without relating to metacognitive components (e.g. Moos & Azevedo, 2008) were also excluded. A total of 54 articles were identified (October 28, 2014), which were mainly published in *Instructional Science*, the *International Journal of Science Education*, and *Computers & Education*.

Three Quantitative Data Analyses

A series of quantitative methods was used to analyze the 54 articles selected. First, the document co-citation analysis (DCA) was treated as an initial step to match all possible co-cited pairs of research articles and to compile the results into a co-citation matrix to identify the intellectual structure in MSiSE research. The relationships among the 54 selected articles were analyzed using their periodical citation data retrieved from the WoS for consistency. For example, White and Frederiksen's (1998) article has a citation record of 359 times on the WoS, but only 292 were cited by journal articles (the rest were cited by conference papers and book chapters). The periodical articles were downloaded. Likewise, the citation data of each selected article was accessed and downloaded from the WoS. A pool of 54 selected articles and their 867 citations (cited by 740 articles) was collected.

A series of data computations and compilations was carried out on the data retrieved to construct the co-citation matrix. First, a symmetric matrix of 54 articles was formed. The co-citation frequency of each cell in the 54 by 54 co-citation matrix was counted as one if the two source articles were jointly referenced in the same citing article (Small, 1973). For instance, Azevedo, R, Cromley and Seibert (2004) and Azevedo, Cromley, Winters, Moos and Greene (2005) are two selected articles which have been cited 93 and 55 times, respectively. Among these citations, 27 articles have jointly referenced the research pair of Azevedo et al. (2004) and Azevedo et al. (2005). Therefore, the raw co-citation value of this research pair in the co-citation matrix is 27. Likewise, the co-citation frequencies were determined for all the research pairs among the 54 MSiSE articles.

Based on the initial results of co-citation computation, 20 of the 54 articles considered were cited only once while 7 were not cited at all; since they could not be analyzed, they were deleted from further consideration, leaving the remaining 27, which have all been co-cited at least once, for selection as the core articles of MSiSE research.

Second, the social network analysis (SNA) was utilized as a visual representation tool to graphically characterize the co-citation structure of the 27 core articles. SNA is a technique for investigating social structures using network and graph theories. It characterizes network structures in terms of nodes (i.e. documents within the network) and the links or ties (relationships or interactions) that connect them. The major contribution of SNA is to provide a novel approach to visualizing the most prominent works in a network. The visualization of co-citation profiles in this study was performed using the spring embedding algorithm built in UCINET (Borgatti et al., 2002). This is a graph-drawing algorithm that seeks the optimal location with minimal stress to position nodes in the network. Further information about the algorithm for drawing networking diagrams can be found in Kamada and Kawai (1989).

Third, exploratory factor analysis (EFA) was performed to facilitate further exploration of the underlying co-citation pattern in the MSiSE research network. EFA is usually used to extract the underlying common factors within the intellectual structure of the literature in co-citation research (White & Griffith, 1981). The input data of the raw co-citation matrix for EFA was converted into a Pearson correlation matrix (with the correlation coefficients ranging from −1 to 1) to minimize the scale effect of the raw co-citation counts (White, 2003). Moreover, based on the multivariate statistical results, the use of EFA is advantageous in terms of providing statistical evidence for understanding the latent structure of the MSiSE literature, including the overall percentage of variance explained by extracted factors and the coefficient for each specific core article loading on the extracted factors. Some of the core subfields within the MSiSE literature can be revealed in the extracted factors identified using the criterion of eigenvalue greater than 1 and named based on those high-loading articles by field experts. Despite being criticized as a less accurate criterion, the Kaiser criterion of retaining factors with eigenvalues greater than one appears to be the most appropriate (Kim & Mueller, 1978). The EFA should reveal the salient subgroups within the 27 core articles in the network, providing further statistical insights for the classification of MSiSE research.

The combination of a co-citation network and EFA can provide an innovative approach to reviewing the most referenced research articles and main themes in the

MSiSE area. Moreover, the main ideas within the core MSiSE research pairs can be examined using the current citing references. Through analyzing these relationships from the population of citing authors, researchers have opportunities to access other researchers who previously may have been unknown to them (Otte & Rousseau, 2002).

Results and Discussion

The major findings from the three analyses are reported. The results of the co-citation computation, networking visualization and exploratory factor analysis are provided and discussed in order of the research foci.

Results of the Co-citation Analysis

The co-citation analysis was conducted based on 27 articles selected and their 740 citing references (authors citing the sample articles). Specifically, 27 core articles were listed in both row and column of a symmetric matrix, and the number of co-citations for the pairs of core articles in the cell were determined and counted for all 740 references. As a result, a total of 434 co-citations (authors citing pairs of the 27 core articles) were found.

Seven highly co-cited MSiSE research studies were identified. The two highest referenced research ties were the pairs of Azevedo et al. (2004, 2005), and White and Frederiksen (1998) and Davis (2003), with 27 and 15 co-citations, respectively. The other five highly referenced research pairs (each co-cited at least five times) are Azevedo et al.'s (2004) with Choi, Land and Turgeon (2005), Azevedo et al.'s (2005) with Puntambekar and Stylianou (2005), and another three studies connected with White and Frederiksen's (1998) (i.e. Azevedo et al. (2004), Manlove, Lazonder and de Jong (2006), and Keselman (2003)). Small (1973) suggested that the higher the number of co-citations, the more likely it is that the paired source documents are bibliographically similar.

These seven highly co-cited MSiSE research pairs have tight literature relationships within each pair of studies based on their follow-up citers' view. The research of Azevedo et al. (2004) and Azevedo et al. (2005) was the highest co-citation pair, endorsed by 27 citing articles of which 17 were by Azevedo's research team because SRL was their on-going research agenda from 2005 to 2011. Note that some recent research reviews have extended the issue of SRL to the context of computer-based learning environments. The other six highly co-cited research pairs, however, were mainly followed by independent researchers. While follow-up citations from original research team members may count as self-citation, all of them met the acceptance criteria of high-quality journals.

Results of the Social Network Analysis

The co-citation network is visualized (Fig. 1) with the 27 articles denoted as nodes and every co-citation link as a line in the network. The social proximity of articles can be represented in terms of number, length, and strength of paths that connect nodes in

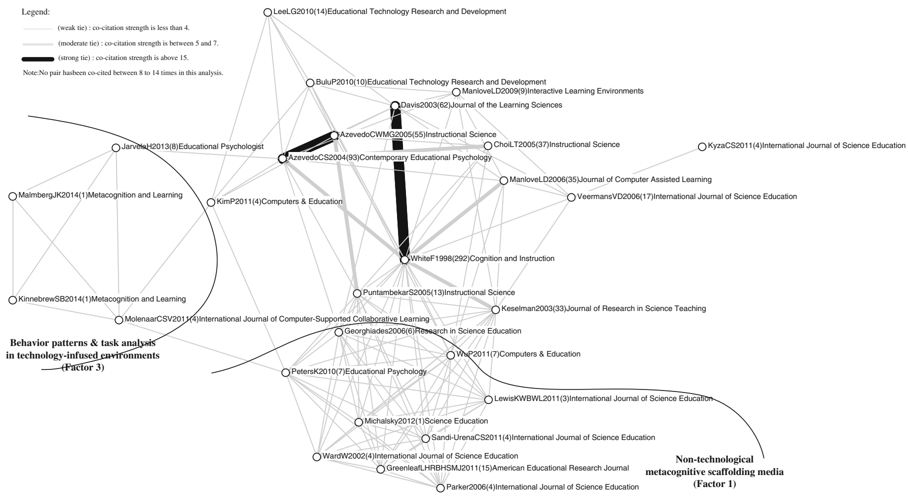

Fig. 1 The co-citation network of metacognitive scaffolding in science education research

networks. Two articles are considered to be proximate if, and only if, they are directly tied in a network (Wasserman & Faust, 1994). The distance (geodesic distance) of two nodes in a network graph is the length of the shortest path. The thickness of the co-citation ties shown in the diagram represents the weights of different co-citation links.

The results of co-citation analysis, seven tight links, illustrated in the center of the co-citation network, were highlighted from a networking perspective. First, the two research pairs which have been co-cited more than 15 times were denoted as two strong links with solid black lines (strong ties), representing the most frequently referenced issues in MSiSE studies. Next, the other five links with solid gray lines stand for the co-citation strength of the ties ranging from 5 to 7 (moderate ties). No pairs with co-citation strength between 8 and 14 were found in this analysis. The remaining links with dotted gray lines mean the strength of the ties among the nodes was less than 5 (weak ties).

The visualization result leaves several important theoretical clues for MSiSE research. First, one of the two most-referenced nodes of the MSiSE research pairs is from the series of studies by Azevedo and colleagues (receiving 27 co-citations), which were published in *Contemporary Educational Psychology* (Azevedo et al., 2004) and in *Instructional Science* (Azevedo et al., 2005). The Azevedo et al. (2004) study compared the effects of adaptive scaffolding, fixed scaffolding, and no scaffolding conditions on 51 undergraduate students' learning about the human circulatory system represented in a hypermedia learning environment. The adaptive scaffolding condition used a human tutor present in the students' learning session to provide guidance and facilitate the students' self-regulated learning using the hypermedia resources. The tutor helped the students think about learning goals and enact aspects of self-regulated learning such as planning their learning, monitoring their understanding, and employing learning strategies. The fixed scaffolding condition provided only the overall and subsequent learning goals as scaffolding. They also found that the students in the adaptive scaffolding condition were more able to regulate their learning and performed better on the posttests.

The same experimental procedure was used in Azevedo et al. (2005) but with a larger sample (n=111) of adolescent students (53 tenth-grade and 58 seventh-grade students). Similar results were found, namely that adaptive scaffolding aimed at facilitating students' self-regulated learning with hypermedia was the most effective. These studies provided not only solid evidence for the positive impact of adaptive scaffolding for self-regulated learning on students' conceptual understanding and regulatory behavior but also a framework for analyzing self-regulated learning behavior.

Second, the other highly co-cited nodes published in *Cognition and Instruction* (White & Frederiksen, 1998) and the *Journal of the Learning Sciences* (Davis, 2003) have been co-cited 15 times (presented as a black solid line in Fig. 1). These two studies both emphasize the scaffolding metacognition of younger students (i.e., middle school students) in online science inquiry learning environments. Specifically, the scaffoldings in the studies were provided through forms of formative assessments, including reflective assessment (White & Frederiksen, 1998) and prompts for reflection (Davis, 2003). The formative assessments were part of the curricular materials provided through handouts or embedded in the online environment, rather than by instructors, and served to help conceptualize and realize what it means and how it looks to scaffold metacognition in inquiry-based science classrooms. White and Frederiksen (1998) provided evidence that students' learning was greatly facilitated by reflective assessment, given that the students in the condition including reflective assessment outperformed the students in the controlled condition without it. Davis (2003) compared the effects of generic versus directed prompts and found that the students who received generic prompts developed more coherent conceptual understanding than did those who received directed prompts. Such a finding indicates that more open-ended prompts may empower students' thinking, resulting in better effects.

Three of the five moderate co-citation pairs (co-cited at least five times) have connections with the White and Frederiksen (1998) study, extending the issue of designing metacognitive scaffolding to focus on (1) facilitating a specific aspect of inquiry skills, such as the meta-level and performance-level of understanding multivariable causality (Keselman, 2003), (2) supporting collaborative scientific inquiry learning (Manlove et al., 2006), and (3) employing adaptive scaffolding (Azevedo et al., 2004). The other two moderate co-citation links connect the studies by Azevedo and colleagues (2004, 2005) with Choi et al. (2005), and Puntambekar and Stylianou (2005), respectively. These two studies extended the issue of designing adaptive scaffolding for self-regulated learning to consider how to support peer-questioning strategies in online group discussion learning environments and navigation behaviors in hypertext learning systems. This extension has broadened the knowledge about adaptive scaffolding of self-regulated learning in some technology-enhanced multimedia learning environments.

Compared with the above tightly connected nodes, studies not yet strongly co-cited also illustrate some diverse research interests in MSiSE. Bulu and Pedersen (2010) compared the effects of domain-general versus domain-specific scaffolds on students' conceptual understanding and problem solving performances in a hypermedia learning environment. The domain general scaffolds include prompting questions for self-regulated learning, whereas the domain-specific scaffolds focus on conceptual and cognitive prompts. Veermans, van Joolingen and de Jong (2006) examined the role of implicit versus explicit heuristic support in facilitating discovery learning in a simulation-based learning environment. Manlove, Lazonder and de Jon (2009) investigated whether working in pairs or individually would have effects on the students' learning and use of regulative tools. These studies extend the central issue of the designs and effects of metacognitive or regulative scaffolds to consider other issues such as the development of learning heuristics, the domain-general versus domain-specific issue, and the role of peer collaboration. The study by Kim and Pedersen (2011) touched on the central issue, but appears in a leading e-learning journal, which seems to have a bridging role in the web to help connect the communities of science education and learning technology. Overall, these central co-citation studies indicate what major issues have been investigated and how they have evolved, as well as some diverse research interests in designing scaffolding for metacognition or self-regulated learning.

Results of the Exploratory Factor Analysis

The EFA provides a complementary approach to exploring and viewing the potential research groups within a co-citation network for recently developing issues without heavy co-citations that were hard to directly map out on the co-citation network diagram. Therefore, the EFA results of the co-citation network help researchers identify emerging issues in addition to mature research topics indicated with thick co-citation links in SNA.

The raw co-citation matrix was converted into a Pearson correlation matrix to minimize the scale effect of raw co-citation counts on the EFA (White 2003). For example, the cell in the raw matrix for the co-citation pair of Azevedo et al. (2004) and Azevedo et al. (2005) was 27, which was converted into a correlation coefficient equal to +0.91. Next, the transformed matrix was factor-analyzed using the FACTOR module (including principal component analysis and varimax rotation) in SPSS. The EFA resulted in six common factors with eigenvalues greater than 1, accounting for 88 % of total variance explained (31, 15, 14, 13, 9, and 6 % for factors 1–6). The first factor consists of 9 articles, the second of 5, followed by 4, 4, 3, and 2 articles for factors 3 to 6, respectively.

The factor naming was based on the assessment of the research areas represented by articles within factor or with the largest factor loadings, and the terminology used in MSiSE research. An inspection of the articles within each factor revealed some consistent and convergent concepts within factors 1 and 3, but not with the other four factors for the factor naming. Linking the EFA results to the network structure revealed a clustering phenomenon of factors 1 and 3 with articles that were relatively new (mostly published after 2010) while those seven highly co-cited pairs of MSiSE studies (scattered among the factors 2, 4, 5, and 6) were published earlier. Thus, factors 1 and 3 were identified as emerging themes—"non-technological metacognitive scaffolding media" and "behavior patterns & task analysis in technology-infused environments."

The nine recent articles in factor 1 involved implementing metacognitive scaffolding through paper-based and/or human activities, such as giving worksheets with written metacognitive prompts (Lewis et al., 2011; Michalsky, 2012; Peters & Kitsantas, 2010), writing reflective journals (Parker, 2006), or engaging learners in teacher-led or student-led activities (Georghiades, 2006; Greenleaf et al., 2011; Sandi-Urena, Cooper & Stevens, 2011; Ward & Wandersee, 2002). Technology, however, played only a minor role in this factor.

The four most current studies in factor 3 (Jarvela & Hadwin, 2013; Kinnebrew, Segedy & Biswas, 2014; Malmberg, Jarvela & Kirschner 2014; Molenaar, Chiu, Sleegers & van Boxtel 2011) involved utilizing computational algorithms to analyze learners' conversation or behavior analyses in computer-based learning environments. Factor 3 demonstrated a recent research focus on "behavior patterns & tasks analysis" where all studies were conducted in computer-based learning systems and applied computational algorithms to analyze students' behaviors and coached cognitive/ metacognitive practices, specific strategy use, or collaboration. This may help overcome some technological and methodological challenges, such as revealing how metacognitive skills are unfolded and socially shared during peer-led or teacher-led scaffolding, or how task characteristics and features of metacognitive scaffolding facilitate various aspects of learning outcomes.

It is also interesting to note that there is no highly co-cited research pair within the cluster of the two emerging factors. Unlike the pattern of the co-citation network in the central cluster, a lack of some thick co-cited ties may suggest that new research foci have not yet emerged in these two research groups. One possible explanation for this pattern may be related to the diversity of researchers' interests in their targeted learners and their concern about the effects resulting from the implementation of metacognitive scaffolding. These diverse interests may also reflect some theoretical assumptions when studying MSiSE: researchers in this field generally accept that metacognition should be studied in the context of specific scientific disciplines and concepts.

The two emerging research trends may also open a window for future research to explore the dynamic and complex interactions between monitoring and controlling processes during self-regulated learning. Compared with the hot topics of technology-enhanced learning environments, non-technological metacognitive scaffolding tools (e.g. sequence minding methods and conversation analyses) should not be overlooked as they may provide crucial information for designing and implementing adaptive cognitive and metacognitive scaffolding and for determining a better time schedule for fading out these explicit supports. Furthermore, a better design of metacognitive scaffolding may need to be implemented adaptively for different learners' characteristics, task features, and goals.

Conclusion and Limitations

This article introduces computer-based systematic analyses of literature reviews, aiming to identify some critical fundamental foundation studies and emerging research themes. The results of this study revealed seven highly co-cited research pairs and two emerging research themes within a co-citation network of 27 articles from an identified sample of 54 articles on MSiSE. This review complements previous reviews that relied on researchers' deductive observations or prior framework. The results could give readers outside the field or researchers new to the field a descriptive sense of the overall picture of the research in MSiSE over the past 20 years. It can also serve as a roadmap for researchers to examine what perspectives have been included and what have been omitted from their works. Moreover, the network of scholars and works illuminate implicit areas in the metacognitive scaffolds and science education research. Lastly, this quantitative review provides a large-scale platform for further scholarly discussion. The research community may debate the reliability of using the technique to evaluate the scientific impact of a researcher as it takes into account both direct and indirect influences.

The present study provides not only a fresh understanding of the MSiSE research but also presents a research-based platform for further scholarly communication. However, some limitations need to be addressed here. First, some book chapters and conference articles that may present important findings were not considered in the search. Future research can include non-journal type articles to provide a more comprehensive co-citation review study. Next, self-citation is dubious in citation analysis due to the concern of self-aggrandizement. However, some researchers have concluded that there is no difference between the incentive for self-citation and other-citation (Bonzi & Snyder, 1991), while others perceive self-citation as an emphasis on one's research and strengthening of one's knowledge claims and research credibility (Hyland, 2003). The Web of Science considers self-citation to be acceptable up to a rate of 20 % (Fowler & Aksnes, 2007). In this analysis, the highest self-citation rate of Azevedo et al. (2004) is 19.4 %, which is lower than the acceptable rate. Nevertheless, many others are concerned about the manipulation of the number of citations and the distortion of the intellectual structure. Researchers should prudentially ensure their own self-citation rate is not above the average for individual disciplines. Last, both the positive and negative reasons for citations (i.e. supportive and critical Citations) are regarded as equal or are ignored because the co-citation analysis is based on the calculation of citation frequency. A more extensive content analysis for further investigation of the deep meanings of related literature can complement the results of co-citation analysis.

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Core articles are preceded by an asterisk

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