CONCEPTUALIZING SPATIAL ABILITIES AND THEIR RELATION TO SCIENCE LEARNING FROM A COGNITIVE PERSPECTIVE

Abstract. *Science learning requires visuospatial thinking. Accordingly, spatial ability is regarded as the key to learning science well, but its effects are sometimes not as significant as expected. To this end, this research aims to conceptualize spatial abilities and to clarify their relation to science learning based on an analysis of empirical studies. Content analysis of 39 studies showed that (1) intrinsic-dynamic skills are the most frequently measured, (2) the explored science topics mostly involve well-established knowledge, (3) the effects of spatial ability on science achievement are inconsistent, and (4) educational interventions are not always effective in improving students' spatial abilities or science achievement. It is argued that domain knowledge interferes with the study results and that domain-specific spatial ability exists, referring to apply spatial-type and domain-specific knowledge. Supported by cognitive theories and empirical evidence, a model is constructed to exhibit the relations between domain-general and domain-specific spatial ability as well as their effects on science achievement. According to the model, the two spatial abilities functionally partially overlap in the operations of spatial skills, and educational experience and malleable spatial skills are reciprocal; however, improvement in general spatial ability, involving the function of the central executive system, is likely limited.*
Keywords: *domain-generality, domain-specificity, spatial ability, domain knowledge, science learning, educational intervention*

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Introduction

Spatial ability has long been considered the vital cognitive ability tightly linked to science learning because visuospatial thinking is essential for the processes of science learning. Therefore, in science learning materials, visual displays are commonly added to illustrate science concepts such as molecular models, the structure of the earth and plate tectonics, and the changing phases of the moon; Learning these concepts requires spatial ability (Mulholland & Ginns, 2008; Sanchez & Wiley, 2010; Stull, Gainer, Padalkar, & Hegarty, 2016). Numerous studies have pointed out that spatial ability not only influences performances in science learning, but also affects young adolescents who subsequently perform relevant occupations (e.g., Lubinski, 2010; Wai, Lubinski, & Benbow, 2009), highlighting the importance of spatial ability.

Although spatial ability is regarded as key to learning science well, its effects are sometimes not as significant as expected. Some studies have identified significant positive effects of spatial ability (e.g., Ozdemir, 2010; Self & Golledge, 1994), but many studies have failed to find these effects (e.g., Helle, Nivala, Kronqvist, Ericsson, & Lehtinen, 2010; Lopez, Shavelson, Nandagopal, Szu, & Penn, 2014). These inconsistent results may be influenced by students' acquired knowledge from the environment and education. Currently, students are frequently exposed to a digital environment. Visuospatial displays of learning materials are colourful and can be presented as animations or three-dimensional visualizations. In 2005, 'The Cambridge Handbook of Multimedia Learning' was published. Based on previous accumulated studies, this book concludes several learning theories and offers clear guidelines on the general principles of material design in a multimedia environment. However, more than a decade later, how visual displays facilitate learning remains a topic of discussion (see Renkl & Scheiter, 2017 for a discussion). Because illustrations and visual displays are abundant in science learning materials, whether these general principles of multimedia learning are suitable (or inadequate) for science instructional design is a topic worthy of discussion in areas of science education. Before such discussions, the role of spatial abilities and their fundamental relation to science learning should be re-examined from a cognitive perspective, which is the main purpose of the

present research. By reviewing and analysing articles published from 2005 to 2017 that provide empirical evidence, it is hoped that this research can make theoretical contributions, and can shed light on classroom practices and instructional design in a multimedia environment. Three research questions were proposed:

1. What spatial abilities were assessed, and to what extent do these spatial abilities relate to science learning?
2. What science topics were explored, and how well do these topics relate to spatial ability?
3. What research orientations and issues of science learning were discussed, and what additional relationships between spatial ability and science learning can be identified from these analyses?

Theoretical Background

Spatial Ability

Spatial ability refers to individuals' cognitive ability to deal with materials presented in space or to orient themselves in space, including mentally manipulating or recognizing the visuospatial attributes of objects such as shapes, configurations, and positions or searching for them (Carroll, 1993). Earlier discussions of spatial ability relied on the psychometric approach by factor analysis rather than on a clear theoretical background. Therefore, researchers did not reach a consensus on either the definition or the subcomponents of spatial ability (Carroll, 1993; Hegarty & Waller, 2006; Uttal et al., 2013). For example, Michael and colleagues proposed that spatial ability comprises three factors, spatial visualization, spatial relations and orientation, and kinesthetic imagery (Michael, Guilford, Fruchter, & Zimmerman, 1957), while Carroll (1993) adopted a broader viewpoint, namely visual perception, and suggested five major factors: spatial visualization, spatial relations, closure speed, flexibility of closure, and perceptual speed. In addition, spatial factors such as spatial orientation, spatial relations, and spatial visualization are intercorrelated and difficult to differentiate (Carroll, 1993; Hegarty & Waller, 2006). The above problems expose the weaknesses and limitations of exploratory factor analysis (Carroll, 1993; Hegarty & Waller, 2006). Recently, Newcombe and Shipley (2015) employed a new approach based on linguistic, cognitive, and neuro-scientific investigations to re-classify spatial skills. Spatial representations were divided into intrinsic or extrinsic, and spatial tasks were separated into static and dynamic forms, generating four classifications of spatial ability. In the intrinsic-extrinsic distinctions, the intrinsic form concerns only the visuospatial characteristics of the object itself and objects' shapes (for example, recognizing that an object is a spoon or a fork), while extrinsic form concerns the relations among or between objects, such as recognizing the positions of objects relative to other objects. In addition, these spatial representations can be represented statically or dynamically transformed (e.g., bending, rotation, and scaling), yielding static and dynamic distinctions. Because a clear definition exists, in this study, we primarily use the four classifications (i.e., intrinsic vs. extrinsic and static vs. dynamic) to analyse spatial abilities and further review their relation to science learning.

The Close Links between Spatial Ability and Working Memory

Researchers have suggested that performance on spatial ability tests is closely associated with working memory capacity because solving spatial tests involves simultaneously maintaining spatial representations in mind and managing the trade-off between storage and transformation functions (Hegarty & Waller, 2006; Lohman, 1996). In the human cognitive architecture, working memory is a temporary storage system that maintains and processes currently 'work on' information that is consciously selected not from only the long-term memory system but also the environment. (Baddeley, 1996; Baddeley & Logie, 1999). Unlike long-term memory, which has massive capacity, working memory is inherently limited (Baddeley, 1996; Baddeley & Logie, 1999). Early studies noted that the major difference between high- and low-spatial ability individuals is the quality of the maintenance of spatial representations after mental manipulation: low-spatial ability individuals often forget information that is initially visible but is subsequently hidden after rotation (Just & Carpenter, 1985). When participants solved complex spatial tasks, they used strategies to reduce spatial imagery and mental operations that required substantial mental effort (Hegarty, 2010). This viewpoint is supported by a study (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) that employed latent-variable analysis to explore the relations between spatial abilities (i.e., spatial visualization, spatial relation, and visuospatial perceptual speed) and working memory. In Baddeley's (1996) theory, working memory is hypothesized to include multiple components comprising a

supervisory system and two slave systems. The central executive, is called the supervisory system, manages the general-purpose (i.e., not sensory-specific) control of attention. It controls the operation of two slave systems, namely the phonological loop and the visuospatial sketchpad, which are responsible for temporarily holding and processing verbal and visual information, respectively. Miyake et al. (2001) pointed out that the three spatial factors are all closely related to the visuospatial sketchpad, demonstrating why these spatial factors are always correlated with each other as indicated in the above section, However, the degree of central executive involvement varies: spatial visualization, commonly assessed by mental rotation tests, is the most demanding for central executive functions, while the visuospatial perceptual speed is the least demanding. In summary, spatial ability not only indicates 'pure' spatial skills but is also strongly linked to working memory, especially to the visuospatial sketchpad and the central executive system, implying the ability to maintain or transform visuospatial representations and the general-purpose function of attention control.

The Relations of Spatial Ability to Science Learning

Although researchers have noted that spatial ability is related to STEM occupational choices and job performance (e.g., Lubinski, 2010; Wai et al., 2009), the effects of spatial ability on science achievement are varied and complicated (Hinze et al., 2013; Uttal & Cohen, 2012). There are two possible explanations. First, several review papers have suggested that the role of spatial ability is *domain-general* in science learning (e.g., Keehner, 2011; Uttal & Cohen, 2012). They proposed that the effect of spatial ability only appears significant when solving novel tasks; however, this significant effect will gradually disappear after individuals have learned, practised, or become familiar with these science topics. After learning, skilled individuals can directly use acquired and organized knowledge stored in long-term memory to solve problems. Thus, the demands for general spatial ability diminish or even disappear. In other words, the learning achievements of skilled participants are more closely associated with knowledge held in long-term memory than spatial ability. Another explanation suggests that the role of spatial ability is *domain-specific* rather than general. There are various spatial skills, and different science questions require different spatial operations to solve them; thus, these various spatial skills might not equally influence science performance. For example, Rohde and Thompson (2007) proposed that among Carroll's spatial factors, closure speed, flexibility of closure, and perceptual speed seemingly have fewer effects on mathematical performance than spatial relations and spatial visualization. Similarly, Ishikawa (2013) noted that only a specific aspect (not all kinds) of spatial ability is related to a certain part (not all types) of geospatial thinking questions. Keehner, Lippa, Montello, Tendick, and Hegarty (2006) found that spatial visualization skills and learners' performance on simulated laparoscope tasks were still significantly correlated after 3 weeks of surgical training in a virtual environment. It is likely that domain-specific spatial ability exists, which is different from general cognitive ability (Keehner et al., 2006; Keehner, 2011). However, the effects of domain-specific ability on more specific and complex tasks remain unclear (Keehner, 2011). In the field of educational psychology research, most studies focus on the effects of domain-general cognitive skills with less emphasis on the role of domain-specific knowledge (Tricot & Sweller, 2014). Hence, reviewing studies in the practice area of science disciplines might provide an opportunity to clarify the associations among spatial abilities, domain-specific knowledge and science learning.

Research Methodology

Search Strategy

The Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI) from the Web of Science Core Collection database were selected because SCI/SSCI journals have a strictly peer-reviewed mechanism. In the literature search, the Boolean operator AND was used to combine two keywords of spatial ability, "spatial ability" and "visuospatial ability", with six keywords of science learning, science education, science performance, science achievement, academic performance, and academic achievement (2 keywords × 6 keywords, giving a total of 12 combinations), to identify articles from 2005 to 2017. After deleting duplicates, the initial literature search extracted 157 articles.

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Article Selection Process

According to the research purpose, inclusion and exclusion criteria were established to select articles. First, retained articles should provide clear criteria evaluating both variables, spatial abilities and science learning performance, and should discuss the relations between them and provide empirical evidence. As a result of this evaluation, 81 articles (including 19 reviews) were removed by examining the abstracts. Second, considering the aims and generalizations of this review, 15 articles with special samples were eliminated: animals (e.g., mice or dogs), disease (e.g., Parkinson's or Alzheimer's disease) and special populations (e.g., the blind or those with disorders). Third, 22 articles discussing non-science disciplines (e.g., design, and aviation) were excluded. Finally, 39 articles were identified for analysis.

Analysis and Coding Procedure

To answer the first research question, spatial abilities were classified primarily based on the four classifications proposed and defined by Newcombe and Shipley (2015): *intrinsic and dynamic, extrinsic and dynamic, intrinsic and static,* and *extrinsic and static* skills. Notably, *mental rotation,* which originally belonged to the intrinsic-dynamic skill, was extracted as an independent classification because more than half of the articles used it. Mental rotation tests assess the ability to mentally rotate objects consisting of two forms: three-dimensional blocks (e.g., cube comparison and Purdue visualization of rotation tests) or two-dimensional plane figures (e.g., card rotation and rotating shapes test). Because the above four classifications are insufficient to encompass all types of tests used in empirical studies, we added three classifications. *Spatial/abstract reasoning* tests refer to tests generally used to assess non-verbal intelligence (e.g., Raven's matrices and non-verbal reasoning skills). In addition, three articles used *science problems requiring spatial operations* as spatial ability. Two articles used *uncommon* tests: Fernandez et al. (2011) choose tests relevant to clinical practices (scanning, categorical and metric tasks), and the tests of Stefanidis et al. (2006) were relatively rarely used (Rey figure and map planning). Third, based on the main conclusion, every paper was divided into two categories (i.e., *significant or non-significant*) regarding the relations between spatial ability and science learning. Some articles used more than one assessment and found inconsistent results; these were double-coded and underlined. For example, Sanchez and Wiley (2014) found that dynamic spatial ability significantly correlated with science text comprehension, whereas paper folding did not. The content analysis of 39 articles in terms of spatial abilities and their effects on science learning (significant or not) is shown in Table 1.

Table 1

Various spatial abilities and their relations to science learning

Spatial ability	The relations between spatial ability and science learning	
	Significant	**Non-significant**
Intrinsic and dynamic: mental rotation	S. C. Chen et al. (2015), Falvo and Suits (2009), Fiorella and Mayer (2017), Hinze et al. (2013), Ishikawa (2013), Karacop and Doymus (2013), Lei et al. (2009), Mayer et al. (2014), Merchant et al. (2012), Olimpo et al. (2017), Ozdemir (2010), Päßler and Hell (2012), Piburn et al. (2005), Sanchez (2012), Schönborn et al. (2011), Stefanidis et al. (2006), Stieff et al. (2014), Van Nuland and Rogers (2017); Vorstenbosch et al. (2013), Wang et al. (2017), Wu et al. (2013), Zhang et al. (2017)	Y. C. Chen and Yang (2014), Fernandez et al. (2011), Ishikawa (2013), Keedy et al. (2011), Lopez et al. (2014), Stefanidis et al. (2006), Stieff (2007), Stull et al. (2012), Sweeney et al. (2014), Wang et al. (2017), Wu et al. (2013), Zhang et al. (2017)
Intrinsic and dynamic	Al-Balushi et al. (2017), Fiorella and Mayer (2017), Ishikawa (2013), Lee and Wong (2014), Ozdemir (2010), Piburn et al. (2005), Sanchez (2012), Sanchez and Wiley (2010), Sanchez and Wiley (2014), Stieff et al. (2014), Wang et al. (2017), Wilhelm (2009), Wu et al. (2013)	Al-Balushi et al. (2017), Ishikawa (2013), Leutner et al. (2009), Sanchez and Wiley (2014), Stefanidis et al. (2006), Sweeney et al. (2014), Wang et al. (2017), Wu et al. (2013), Zhang et al. (2017)
Extrinsic and dynamic	Wilhelm (2009)	Sweeney et al. (2014)

The relations between spatial ability and science learning		
Spatial ability	Significant	Non-significant
Extrinsic and static	N/A	Helle et al. (2010), Zhang et al. (2017)
Spatial/abstract reasoning	Päßler and Hell (2012), Wilhelm (2009)	Lei et al. (2009), Stefanidis et al. (2006)
Science problems requiring spatial operations	Cole et al. (2015), Hoyek et al. (2014), Mohamed-Salah and Alain (2016)	Hoyek et al. (2014), Mohamed-Salah and Alain (2016)
Uncommon	Fernandez et al. (2011)	Fernandez et al. (2011), Stefanidis et al. (2006)

In response to the second research question, the science topics explored in each study and their relations to spatial ability (significant or non-significant) were analysed as shown in Table 2. Articles involving two disciplines/topics were listed repeatedly (e.g., Ozdemir, 2010; Zhang, Hu, Ren & Fan, 2017). Articles with inconsistent results were underlined.

Table 2
Disciplines and science topics explored in empirical studies

The relations between spatial ability and science learning		
Disciplines	Significant	Non-significant
Chemistry	**Atomic orbitals** (S. C. Chen et al., 2015), **chemical bonding** (Karacop & Doymus, 2013; Ozdemir, 2010), **chemistry** (Al-Balushi, et al., 2017), **dissolution in water at the molecular level** (Falvo & Suits, 2009), **dynamic fluid equilibrium** (Hinze et al., 2013), **molecular models** (Merchant et al., 2012; Mohamed-Salah & Alain, 2016; Ozdemir, 2010; Schönborn et al., 2011), **organic chemistry** (Stieff et al., 2014)	**Chemical bonding** (Leutner et al., 2009; Lopez et al., 2014), **molecular model** (Mohamed-Salah & Alain, 2016; Lopez et al., 2014; Stieff, 2007, Stull et al., 2012), **organic chemistry** (Lopez et al., 2014; Stieff, 2007; Stull et al., 2012)
Basic Medical Sciences/ Biology	**Anatomy** (Fernandez et al., 2011; Hoyek et al., 2014; Van Nuland & Rogers, 2017; Vorstenbosch et al., 2013), **human respiratory system** (Fiorella & Mayer, 2017; Wu, et al., 2013), **laparoscopic skills training** (Stefanidis et al., 2006), **life science** (Zhang et al., 2017), **mRNA synthesis** (Olimpo et al., 2017)	**Anatomy** (Fernandez et al., 2011; Hoyek et al., 2014), **human respiratory system** (Wu, et al., 2013), **laparoscopic skills training** (Stefanidis et al., 2006), **microscopic pathology** (Helle et al., 2010)
Earth Sciences	**Geospatial thinking** (Ishikawa, 2013; Piburn et al., 2005), **GIS landmark searching** (Lei et al., 2009), **lunar phases** (Cole et al., 2015; Wilhelm, 2009), **mineralogy** (Ozdemir, 2010), **plate tectonics** (Sanchez, 2012; Sanchez & Wiley, 2010; Sanchez & Wiley, 2014)	**Geospatial thinking** (Ishikawa, 2013), **GIS landmark searching** (Lei et al., 2009), **model of earth axial precession and global warming** (Y. C. Chen & Yang, 2014), **plate tectonics** (Sanchez & Wiley, 2014)
Physics	**Motion and collision** (Wang, et al., 2017)	**Motion and collision** (Wang, et al., 2017)
General sciences	**Scientific reasoning** (Mayer et al., 2014)	**Scientific reasoning** (Al-Balushi, et al., 2017)
Mixed	**Choice of major in the sciences (biological science, computer science, mathematics, physical science)** (Päßler & Hell, 2012)	**Earth and physical science** (Zhang et al., 2017)

As for the third research question, the 39 studies can be roughly divided into two research orientations: *learning performance* and *educational interventions*. *Learning performance* comprises two issues in terms of academic

aptitude and science achievement. *Educational interventions* also involve students' achievement and comprise three issues: through instruction, whether spatial ability can be enhanced, whether science achievement can be improved, and whether the impacts of spatial ability on science achievement can be reduced. Notably, because experts are individuals who are educated and who have practised in a discipline, studies comparing experts and novices in a specific domain were included in the educational interventions. Table 3 shows the coding framework and the analysis results. Articles with inconsistent findings for the same issue were underlined, and those with more than one research orientation/issue were listed repeatedly (e.g., Fernandez et al., 2011; Piburn et al., 2005). During the process of analysing studies and articles with the above three coding frameworks, to establish coding reliability, all differences were resolved by three researchers who worked collaboratively and discussed the issues to reach consensus.

Table 3

Research orientations of articles and the discussed issues

Research orientations	Significant findings	Non-significant findings
Learning performance	**(1) the impacts of spatial ability on academic aptitude in science**	
	Fernandez et al. (2011), Päßler and Hell (2012), Vorstenbosch et al. (2013)	Fernandez et al. (2011)
	(2) the relations between spatial ability and science achievement	
	Fiorella and Mayer (2017), Hinze et al. (2013), Ishikawa (2013), Lei et al. (2009), Mayer et al. (2014), Merchant et al. (2012), Olimpo et al. (2017), Ozdemir (2010), Sanchez and Wiley (2014), Stefanidis et al. (2006), Stieff et al. (2014)	Y. C. Chen and Yang (2014), Helle et al. (2010), Ishikawa (2013), Lei et al. (2009), Leutner et al. (2009), Lopez et al. (2014), Sanchez and Wiley (2014), Sidhu et al. (2004), Stefanidis et al. (2006)
Educational interventions	**(1) (science curriculums) can enhance spatial ability**	
	Al-Balushi et al. (2017), Cole et al. (2015), Fernandez et al. (2011), Merchant et al. (2012), Mohamed-Salah and Alain (2016), Ozdemir (2010), Piburn et al. (2005), Vorstenbosch et al. (2013), Wilhelm (2009)	Fernandez et al. (2011), Ishikawa (2013)
	(2) (visuospatial materials) can improve science achievement	
	S. C. Chen et al. (2015), Cole et al. (2015), Falvo and Suits (2009), Hoyek et al. (2014), Karacop and Doymus (2013), Lee and Wong (2014), Merchant et al. (2012), Mohamed-Salah and Alain (2016), Piburn et al. (2005), Sanchez (2012), Sanchez and Wiley (2010), Schönborn et al. (2011), Stefanidis et al. (2006), Stieff et al. (2014), Van Nuland and Rogers (2017); Wang et al. (2017), Wu et al. (2013)	Al-Balushi et al. (2017), Hoyek et al. (2014), Mohamed-Salah and Alain (2016), Wu et al. (2013)
	(3) can reduce the impacts of spatial ability on science achievement	
	Fiorella and Mayer (2017), Helle et al. (2010), Keedy et al. (2011), Stieff (2007), Stull et al. (2012), Sweeney et al. (2014), Wang et al. (2017)	Fiorella and Mayer (2017), Wang et al. (2017)

Research Results

Spatial Abilities in Empirical Studies and Their Relations with Science Learning

Three findings are worth noting. First, Table 1 shows that spatial abilities vary, and intrinsic-dynamic skills, especially mental rotation, are of the greatest interest to researchers. Fewer studies use extrinsic and static types of tests, and no studies measured intrinsic-static tests. Second, as long as tests embraced non-verbal types or possessed spatially presented information, they could be regarded as spatial ability tests. Examples include Raven's matrices test and abstract reasoning skills, which were typically used to assess non-verbal intelligence, and even learning assessments that involved solving science questions requiring spatial operations. Therefore, there were many underlying meanings of the term 'spatial ability' in empirical studies of science learning. These involved general cognitive ability, spatial skills (intrinsic-extrinsic and static-dynamic spatial skills), and the ability to solve science problems requiring spatial thinking. Using the general term 'spatial ability' obscured these details. Third, regardless of the type of spatial ability, the studies did not always find significant results as expected. Moreover, 12 underlined articles reported inconsistent findings, revealing that the significant effects of spatial ability on science learning are conditional subject to spatial ability choices and the content of the tasks performed. For example, some studies proposed that only certain spatial abilities are vital (e.g., Ishikawa, 2013; Lei, Kao, Lin, & Sun, 2009; Sanchez & Wiley, 2014) or suggested that the task demands influence the study results (e.g., Hoyek et al., 2014; Mohamed-Salah and Alain, 2016; Stefanidis et al., 2006).

Disciplines and Science Topics Explored in Empirical Studies

Table 2 shows that chemistry (19 articles) was the most common discipline exploring spatial ability and science learning, followed by basic medical sciences/biology (11 articles), earth sciences (10 articles), general science (2 articles) and mixed (2 articles), and physics (1 article). The explored science topics were limited, but even with regard to an identical topic, the effects of spatial ability were not stable. Chemistry focused on invisible microscopic phenomena, whereas biological and medical sciences primarily concentrated on the configuration of internal organs and the functional mechanisms of the body, some of which were microscopic, such as the structure of RNA and microscopic pathology. In earth sciences, astronomy and geology/geography were of the areas of greatest interest. Only one topic, motion and collision, was found in physics. Four articles (Al-Balushi, Al-Musawi, Ambusaidi & Al-Hajri, 2017; Mayer, Sodian, Koerber & Schwippert, 2014; Päßler & Hell, 2012; Zhang et al., 2017) aimed to identify the more general effects (i.e., across science domains) of spatial ability. The content of these explored topics primarily involved well-established scientific knowledge (e.g., scientific theories, principles, laws or models), such as molecular orbital theory, valence bond theory and valence shell electron pair repulsion in chemistry, energy conservation law and Newton's laws of motion in physics, and plate tectonics, models of the earth's axial precession, and phases of the moon models in earth sciences.

Research Orientations and Issues Discussed in the Articles

Table 3 reveals that the effects of spatial ability on academic aptitude are much more stable than on science achievement. Two studies focusing on academic aptitude reported significant findings. Vorstenbosch et al. (2013) proposed that individuals with science-related majors outperformed those with humanities-related majors on mental rotation tests. Students whose spatial abilities were better than their verbal abilities tended to choose science majors (Päßler & Hell, 2012). However, Fernandez et al. (2011) found that experts, intermediates, and novices in anatomy did not outperform non-anatomy majors in all types of spatial abilities but only in categorical spatial judgement tasks. In contrast, several studies focusing on science achievement proposed that only certain spatial abilities have significant effects, as mentioned in the previous section.

In terms of the effectiveness of educational interventions, numerous studies have determined that science curricula are effective in improving spatial ability, with the exception of two studies. Ishikawa (2013) showed that experts' intrinsic-dynamic spatial abilities were not better but were even worse than those of novices, most likely because of ageing. Fernandez et al. (2011) proposed that not all types of spatial ability could be improved. With regard to the second issue, most studies reported that science achievement could be improved through the assistance of visuospatial materials, such as animations (Falvo & Suits, 2009; Hoyek et al., 2014; Karacop & Doymus,

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2013), video games (Sanchez, 2012), virtual reality (Lee & Wong, 2014; Piburn et al., 2005; Schönborn, Bivall & Tibell, 2011) and mobile applications (Wang, Wu & Hsu, 2017). Four studies (Falvo & Suits, 2009; Piburn et al., 2005; Sanchez & Wiley, 2010; Stieff et al., 2014) mentioned that support from appropriate materials could bridge the gender gap. Three articles exhibited inconsistent effects. Hoyek et al. (2014) noted that 3D animation only improved performance on questions requiring spatial manipulation rather than all types of questions. Mohamed-Salah and Alain (2016) argued that although the use of concrete models promoted spatial thinking, the effect of concrete models was influenced by students' familiarity with different representations and the complexity of the molecular representations. Wu, Lin, and Hsu (2013) proposed that different representation sequences had effects only on the learning of higher spatial ability students, who outperformed on conceptual and spatial knowledge and showed advantages when static illustrations were presented first before dynamic ones. Only one study did not find significant effects of digital instruction on scientific reasoning ability (Al-Balushi et al., 2017). With regard to the third issue, most studies found that educational interventions could narrow the performance gap between high and low spatial ability groups. That is, after instruction, the impacts of spatial ability on science achievement were no longer significant. For example, Stieff (2007) deliberately taught analytical strategies to students who initially used mental rotation and found that they had equal success, implying that instruction could reduce the impact of spatial ability. He also found that novices tended to use mental rotation strategies while experts selectively used analytical strategies to solve organic chemistry problems, suggesting that the effects of spatial ability were only significant for beginning students or novel tasks. Wang et al. (2017) reported that mobile applications with multi-touch features and multi-touch and tilt features were more effective, while computer simulations were not. Fiorella and Mayer (2017) found that reading a scientific text by a note-taking medium on a computer was more effective than using paper and a whiteboard.

To sum up, educational interventions were not always effective in terms of improving spatial ability or science achievements, depending on factors such as the demands and complexity of science tasks, students' familiarity with science topics, and the modality of instruction (e.g., representation sequences). Furthermore, the impacts of spatial ability on science achievement were not fixed and were influenced by instruction (e.g., specific strategies taught or training, note-taking, and uses of mobile applications).

Discussion

Domain-General or Domain-Specific Role of Spatial Ability in Science Learning

The generality and specificity of spatial ability exist simultaneously in empirical studies of science learning. An evident example of generality is non-verbal intelligence tests, which are typically psychometric measures of general cognitive ability or general fluid intelligence, referring to the ability to abstractly reason and solve novel tasks across domains (Horn & Cattell, 1967). However, the following examples reveal specificity. The first example comes from studies examining competence in solving spatially demanding science problems as spatial ability. Second, many studies use spatial ability tests that have similar spatial-operating skills with a specific science topic. For example, mental rotation skills are necessary spatial operations for mentally manipulating the representation of molecular structures to understand scientific concepts such as crystal mineralogy, organic chemistry, and mRNA synthesis (e.g., Merchant et al., 2012; Olimpo, Quijas, & Quintana, 2017; Ozdemir, 2010; Stieff, 2014). The cardinal direction test of Wilhelm (2009) asks students to identify the orientation between the self and others, which is similar to the learning topic of lunar phases, which requires recognition of the rising and setting directions of the moon. Third, several studies suggest that not all types of spatial ability are correlated with science learning (e.g., Ishikawa, 2013; Sanchez & Wiley, 2014) or that only specific science problems need spatial ability (e.g., Hoyek et al., 2014; Mohamed-Salah and Alain, 2016; Stefanidis et al., 2006). In most cases, however, it is not easy to identify the role of spatial ability as general or specific.

The generality of spatial ability is probably inherent because performing spatial tasks involves the central executive system and the most frequently used mental rotation tests involve this system to a high degree. The central executive system is closely connected to general fluid intelligence (Heitz, Unsworth, & Engle, 2005; Kyllonen & Christal, 1990). Spatial ability is thus also relevant to non-spatial problems, such as verbal performance (Tolar, Lederberg, & Fletcher, 2009) and reading (Zhang et al., 2017). Moreover, spatial ability implies certain spatial skills, while the generality or specificity of skills is more of a continuum than a dichotomy (Schunn and Anderson, 1999). Spatial ability has effects on only limited science topics, as shown in Table 2, indicating that the range of

application of spatial skills is not broad. Although intrinsic-dynamic skills are frequently measured and seemingly 'general' across different science domains, the types of dynamic simulations (e.g., the path of movement and rotation angles) are not identical across different tasks. The dynamic simulations in a specific task should be constrained by domain knowledge rather than free (i.e., task-specific). The interferences of domain knowledge are discussed in the next section.

Domain-Specific Knowledge Interferes with the Effects of Spatial Ability

The effects of spatial ability on science achievement are inconsistent among studies. Because the explored topics in science mostly involve well-established knowledge, the effects of domain knowledge should be considered in the processes of science learning. The distinction of intrinsic-extrinsic information of spatial representations cannot completely describe the characteristics of visual displays in science materials. Scientific visual representations in learning materials are a form of static declarative knowledge conveying scientific knowledge (e.g., concepts, rules, principles) and are depicted by using certain conventions to concisely represent 3D relations (Hegarty, Carpenter & Just, 1991; Mohamed-Salah & Alain, 2016; Perini, 2005; Stull et al., 2012). For example, the chemical bonding, the bond angles, the arrangement of atoms in crystals, and the crystal structures in mineralogy obey domain-related spatial rules, which are scientifically meaningful and not random. Hence, understanding information-intensive scientific visual representations requires more mental effort than general spatial tasks. This is one reason why learning achievements in science are influenced by the complexity of learning materials.

On the other hand, echoing the former section's discussion, the operations of spatial skills are also influenced by domain-specific knowledge. The types of dynamic simulations across different science topics are not identical, but their operations are necessarily constrained by domain knowledge. For example, the dynamic processes of volcanic eruptions and the changes of moon phases are different; they must obey plate tectonics theory and the sun-moon-earth model, respectively. Consequently, the dynamically manipulated skills in science learning may refer to the idea of 'domain-specific spatial skills' belonging to procedural knowledge, that is, the knowledge of 'how to do', which is the knowledge of motor skills, cognitive skills, and cognitive strategies (Anderson, 2000; Gagné et al., 1993). Because domain-specific spatial skills can be concretely described, they can be learned and taught. Once domain-specific spatial knowledge has been learned, it can be stored in long-term memory and can be automatically retrieved when similar problems are encountered. This is why science achievement is influenced by students' familiarity with tasks (or prior knowledge). When students learn science with visual displays, domain-specific knowledge (both declarative and procedural knowledge) is certainly involved in cognitive processes. However, most empirical studies merely focus on dynamic skills, and these skills are usually necessary for understanding visual scientific representations. Fewer studies discuss the spatial attributes of static science knowledge conveyed by visual scientific representations and symbolic representations.

Reciprocal Relations between Spatial Skills and Educational Experience

The results showed that not only can spatial ability be improved after science curriculum interventions, but science achievement can also be improved through visuospatial-relevant activities or material support. Spatial ability (mostly dynamic skills) and educational experience can improve each other, revealing that their relations are not causal but are correlated and reciprocal. This finding can be explained by Singley and Anderson's (1989) skill-overlap hypothesis, which suggests that prior learning skills can be transferred to another learning topic as long as they share 'identical mental operations'. The above discussions provide additional evidence to support the previous argument that spatial ability in science learning often indicates spatial skills overlapping domain-specific science knowledge. Spatial skills can be taught, can be improved and are malleable. This viewpoint is in line with Uttal et al. (2013). By contrast, whether domain-general spatial ability can be improved by educational experience remains an open question. Through prolonged exposure to a digital learning environment and learning different science topics that require various modes of visuospatial operations, diverse spatial skills can be enhanced. Researchers generally deem the Flynn effect (Flynn, 1998) which refers to the fact that IQ scores increase over time, evidence for the effects of acquired experience on general intelligence (e.g., Ceci, Barnett, & Kanaya, 2003; Martinez, 2000). However, because general spatial ability is closely related to the executive system, which is not bound to any specific sensory modalities, it is likely difficult to improve general spatial ability solely through visuospatial-enriched acquired experience.

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CONCEPTUALIZING SPATIAL ABILITIES AND THEIR RELATION TO SCIENCE LEARNING FROM
A COGNITIVE PERSPECTIVE
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Proposing A Model to Explain the Relationships between Spatial Ability and Science Achievement

Based on the discussion above, we proposed that spatial ability exists in two forms, domain-general and domain-specific. Furthermore, we constructed an evidence-based model to explain the relations between domain-general and domain-specific spatial ability and science achievement, as illustrated in Figure 1.

Figure 1
Relations between Domain-General Spatial Ability and Domain-Specific Spatial Ability and their effects on science achievement
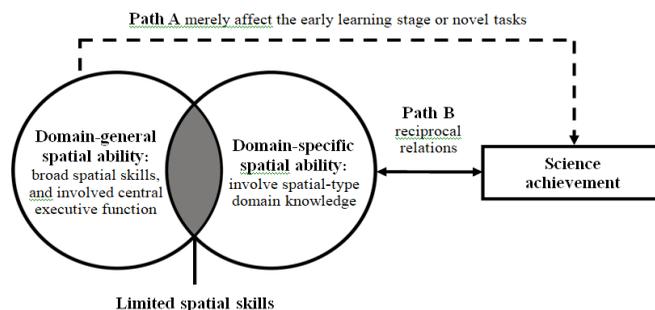
Domain-general spatial ability denotes a general approach or method to deal with materials presented in space or that orient themselves in space (Carroll, 1993); it is closely related to working memory. Domain-specific spatial ability, by contrast, is defined as the ability to solve spatially demanding problems in subject-matter areas. In the science domain, domain-specific spatial ability is a scientific competence that refers to the effective application of spatial-type scientific declarative knowledge (e.g., visual scientific representations, science principles, or rules) and task-relevant spatial skills (e.g., specific spatial skills or manipulation procedures) for solving domain problems. As shown in Figure 1, domain-general spatial ability and domain-specific spatial ability functionally partially overlap (the grey area) because both involve the maintenance, operation, and transformation of spatial representations in mind. The area of overlap mostly involves dynamic spatial skills, especially mental rotation skills in science-related disciplines. They differ in three aspects. First, general spatial ability includes more varied types of spatial skills, while domain-specific spatial ability involves only task-relevant spatial skills, and its operations are necessarily under the constraint of domain knowledge. Second, the function of general-purpose control of attention (central executive function) is exclusive to general spatial ability. Third, the to-be-manipulated visuospatial representations are different: general spatial ability involves geometric graphs, papers or blocks, while domain-specific spatial ability involves visual scientific representations conveying spatial information of domain-specific knowledge. Two paths (A and B) explain how spatial ability influences science achievement. According to the literature (Keehner, 2011; Uttal & Cohen, 2012), domain-general spatial ability has effects only in the early learning stage for novel tasks, and its effects gradually disappear after the domain-specific knowledge acquired, as indicated by path A with the dotted line in Figure 1. Path B, shown with double-sided arrows, represents the reciprocal relations between domain-specific spatial ability and science achievement.

Conclusions and Implications

By reviewing empirical studies published from 2005 to 2017 and explaining the results of the analysis from a cognitive perspective, this research proposed a conceptual model for revealing the distinctions and relations between domain-general and domain-specific spatial ability, and their effects on science achievement. From the viewpoint of education, domain-specific spatial ability is differentiated from the general term 'spatial ability' for the following reasons. First, although the four classifications of spatial ability by Newcombe and Shipley are clearly defined, they were originally developed in the design and creativity domain and remain insufficient for capturing the necessary spatial ability for science learning. Domain-specific spatial ability combining spatial-type knowledge with task-relevant spatial skills can be a better predictor of science learning, whose influences are more direct and powerful than those of domain-general spatial ability. The impacts of domain-general spatial ability are conditional and merely affect the early learning stage or novel tasks. Second, compared with general spatial ability,

whose improvement is partial and limited, domain-specific spatial ability can more directly changeable through educational interventions. Likewise, domain-specific tests of spatial ability should not be called spatial ability tests to avoid confusion with the established definition of this concept.

The proposed model gives rise to theoretical and practical implications. Theoretically, this model provides a cornerstone for further examining how domain-general and domain-specific spatial ability interact with each other, and how they influence science learning. Future interdisciplinary discourse and studies are necessary to explore and discuss the extent to which these two spatial abilities overlap (e.g., the function of imagery storage, spatial-information decoding, retrieval, and retention), which remains unclear. In practice, learning science well is not limited to only those who have excellent spatial ability (identified by psychometric tests) because spatial abilities exist in two forms. Domain-specific spatial ability can be explicitly taught and enhanced. Spatial skills training should be tied to a concrete situation in a science-specific context. As knowledge is acquired, spatial skills are improved. With respect to instructional design, the spatial operations of tasks can be simulated through educational technologies that help to reduce students' cognitive load and to aid those who do not excel at these tasks to further promote students' learning. In addition to the use of educational technologies to present dynamic changes, instructional design should pay more attention to the semantic knowledge of scientific visual representations. Although scientific visual representations are visual displays, their functions are not equivalent to visual perception and visual imagery and should involve domain knowledge. Adding cues in the form of superficial features such as highlights, arrows, and salient labels is insufficient to aid learning, especially for complex and information-intensive scientific visual representations. For the design of learner-centered instruction in scientific disciplines, the underlying domain-specific knowledge implied in the visual displays should explicitly and clearly correspond to the descriptions to reveal the visuospatial-type scientific rules and the scientific meaning of symbols. Such a design is critical but rarely mentioned in the principles of multimedia learning. Lastly, it remains unclear whether the improvement of spatial skills contributes to enrolment and retention in university science-related subjects. This issue merits further examination.

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Note: Papers marked with an asterisk (*) are those selected for the current review

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