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ARTICLE

Exploring Spatial Cognitive Process Among STEM Students and Its Role in STEM Education

A Cognitive Neuroscience Perspective

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Abstract
Spatial ability is a powerful systematic source of individual differences in the areas of science, technology, engineering, and technology (STEM). Abundant research has evidenced that psychometrically assessed spatial ability is a strong predictor of STEM achievement. However, its underlying cognitive process and relevant role in STEM education are unknown. From the perspective of cognitive neuroscience, spatial ability is also considered a human intelligence deriving from the cognitive processing of spatial information in the brain. With the help of the cognitive neuroscience paradigm of spatial navigation, in the present work, we investigate the spatial cognitive process among STEM students and its role in STEM education. A total of 172 undergraduates majoring in veterinary science participated in a spatial navigation test. Participants attempted to return a toy to its original place in an arena when given either internal self-motion cues only, external landmark cues only, or both in a spatial navigation task. Modelling analysis of 172 participants' spatial navigation behaviours showed that all the participants' spatial cognitive processes featured navigation cue integration. The results of the different tests showed that students with higher levels of navigation cue integration had better academic performance in STEM learning. The results also indicated that, surprisingly, better academic performance in science and mathematics relied more on the use of internal self-motion cues, while better academic performance in engineering and technology relied more on the use of external landmark cues. This study sheds some light on the spatial cognitive process and its role in STEM education from the cognitive neuroscience perspective, thus deepening the functional understanding of spatial ability as a systemic source of individual differences for STEM education, and provides an empirical reference point for interdisciplinary studies on the role of cognition in the context of STEM education. Implications on STEM learning design and STEM teaching were discussed.

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1 Introduction

The main goal of STEM education is to promote students' STEM literacy (Zollman 2012), and then to prepare them to face complex challenges in the future real world (OECD 2017; Wai et al. 2009). Therefore, policymakers in many nations have launched powerful STEM-oriented policies and increasingly budgeted a large number of funds into STEM education over the past 10 years, such as STEM 2026 in the USA (Tanenbaum 2016), MINT (Mathematik, Informatik, Naturwissenschaft und Technik) in Germany (Ertl et al. 2017), and LUMA (Luonnontietee and Mathematics) in Finland (Lavonen and Laaksonen 2009). Even though educational interventions and support have been widely applied in the teaching practices of STEM education, it remains that a significant number of students have struggled to achieve in STEM education, which results in high attrition and failure rates (Jones and Burnett 2008; Kranzfelder et al. 2019; Marginson et al. 2013; Uttal and Cohen 2012). To seek answers for effective STEM education, educators have started to turn their attention to intrinsic influential factors i.e. learners' individual differences (Lubinski 2010).

Since STEM fields have a substantial number of spatially oriented tasks, spatial ability, as an important individual difference, has seen a resurgence of interest in recent years (Buckley et al. 2018; Carroll 1993; Chen et al. 2020; Lubinski 2010; Newcombe and Shipley 2015; Uttal and Cohen 2012). As a result, substantial research has focused on uncovering the relationship between spatial ability and educational performance in STEM education. Their findings manifested that students who had psychometrically assessed high levels of spatial ability always outperformed in STEM or STEM-branch learning, such as the changing of lunar phases (Mulholland and Ginns 2008), plate tectonics, and crustal evolution (Sanchez and Wiley 2014), the spatial arrangement of atoms in a molecule (Lopez et al. 2014), calculation and kinematics problems (Cheng and Mix 2014; Kozhevnikov et al. 2007), computer-assisted surgical simulator tasks (Roach et al. 2019), and architecture and interior design (Suh and Cho 2020).

However, even though significant positive relationships between spatial ability and STEM education have been evidenced, why spatial ability has such an effect in STEM is unknown. Recent studies denoted that a bottom-up inductive approach of the kind used in traditional psychometrics and factor analysis failed to propose a clear theoretical background for spatial ability and its underlying cognitive process (Buckley et al. 2018; Chen et al. 2020; Newcombe and Shipley 2015; Uttal and Cohen 2012). Moreover, whether the four branches of science, technology, engineering, and mathematics in STEM education relied to the same extent on spatial ability was also an unexplored area (Buckley et al. 2018; Uttal and Cohen 2012). Thus, scholars went further and claimed that the field needed a new top-down interdisciplinary paradigm to uncover the spatial cognitive process among STEM students and to explain its role in STEM education (Buckley et al. 2018; Newcombe and Shipley 2015; Roach et al. 2019; Uttal and Cohen 2012).

Spatial ability is not only a powerful systematic source of individual differences but also essentially an important human cognitive intelligence (Lubinski 2010). How people process spatial information in real environments has always been a hot research topic in the fields of cognitive neuroscience (Astur et al. 2002; Bellmund et al. 2018; Gil et al. 2018; Maguire et al. 2000; Nardini et al. 2008; Kessels et al. 2011). A recent breakthrough in human spatial navigation revealed the development of human spatial cognition. Although human spatial navigation depended on both external landmarks and internal self-motion cues (e.g., vestibular and proprioceptive) (Astur et al. 2002; Kessels et al. 2011), the ability to integrate internal self-motion cues with external landmark cues nearly optimally to navigate depended on an extended cognitive developmental process (Nardini et al. 2008; Negen et al. 2018). This new paradigm would offer a top-down analysis of the nature of spatial ability in the contexts of STEM education (Buckley et al. 2018; Newcombe and Shipley 2015). As a result, investigations on spatial ability at a fine-grained level can support the development of STEM learning design and STEM teaching to increase their efficacy and relevant effects in STEM education (Buckley et al. 2018).

Scholars' claims for further investigations in spatial ability underlying cognition and the new paradigms in fields of cognitive neuroscience inspired this study. We attempt to adopt a cognitive neuroscience approach to uncover the spatial cognitive process among STEM students and its role in STEM education. A series of three research questions guides the study. The first question, to depict the picture of spatial cognitive process among students in STEM domains, asks (1) "what are the characteristics of spatial cognitive process among STEM students?" Based on the first question, the second question is designed to confirm the difference in academic performance in STEM education between students with high and low spatial cognition. Specifically, it examines (2) "whether academic performance in STEM education is associated with spatial cognitive process?" The curiosity drives this study to further explore students' spatial strategic utilization on the four branches of STEM education, asking, (3) "whether academic performances in the four branches of STEM education are associated with a particular spatial cognitive process?"

2 Literature Review

2.1 The Importance of Spatial Ability in STEM Education

Spatial ability, a component of human cognitive intelligence (Carroll 1993; Toivainen et al. 2018), is described as the individuals' capacity 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). In everyday situations, people are challenged to deal with perceived spatial information when they navigate the three-dimensional world. They have to mentally represent the spatial information, transform it, check it, and often recall it after time has passed. This is manifested practically in countless routine tasks, such as parking a vehicle in a narrow garage, recalling where to find gadgets on the shelf, or relating a map to the road ahead of us. Some individuals excel at manipulating spatially oriented tasks, while others find it difficult. Superior performance in these tasks is attributed to individuals' spatial ability (Carroll 1993; Lohman 1979; Roach et al. 2019; Uttal et al. 2013).

Beyond parking a vehicle, location recalling, and way-finding, a substantial number of tasks in STEM domains were also spatially oriented, requiring students, specifically novice learners, to focus on the spatial nature of the tasks and underlying cognitive processes (Hegarty et al. 2006; Kozhevnikov et al. 2007; Newcombe and Shipley 2015). For instance, the tasks in STEM domains included identifying, describing, and classifying the shape, position, and orientation of objects (e.g., the spatial arrangement of atoms in a molecule, Lopez et al. 2014); manipulating spatial representations in the form of graphs, diagrams, or scientific (engineering) models (e.g., composing an engineering graph according to clients' request, Kozhevnikov et al. 2007); envisioning the processes of objects' motion in three-dimensional coordinates (e.g., demonstrating the changing of lunar phases to explain the lunar eclipse phenomenon, Mulholland and Ginns 2008); and using spatial-thinking strategies to think about non-spatial phenomena (e.g., using network analysis for visualising social interactions, González-Howard 2019). Thus, spatial ability receives high expectations for the development of STEM expertise and creative accomplishments. Lubinski (2010) had described it as a sleeping giant for talent identification and development in STEM domains.

Due to its promising excellent properties, educators and practitioners have carried out empirical studies to explore the role of spatial ability in STEM or STEM-branch education (Buckley et al. 2018; Cheng and Mix 2014; Jones and Burnett 2008; Kozhevnikov et al. 2007; Marunic and Glazar 2013; Newcombe 2017; Pittalis and Christou 2010; Roach et al. 2019; Small and Morton 1983; Suh and Cho 2020; Wai et al. 2009; Wu and Shah 2004). For example, Kozhevnikov et al. (2007) conducted a series of studies to examine the relation of spatial ability to solving kinematics problems that included either predicting the two-dimensional motion of an object, converting one frame of reference to another, or interpreting kinematics graphs. In the first study, sixty novice students from the physics major completed kinematics problem tests and psychometric tests of spatial visualisation. In the second study, seventeen additional students (8 students with high spatial ability and 9 students with low spatial ability) participated in think-aloud protocols as they solved the kinematics problems. In contrast to students with high spatial ability, most students with low spatial ability could not combine two motion vectors and failed to translate frames of reference to meaningful kinematics graphs. His finding suggested a significant correlation existed between spatial ability and solving kinematics problems with multiple spatial parameters.

The positive effects of spatial ability on academic performance have also been proved in the context of more complex STEM learning. For example, fifty-four novice dental students in a university hospital were enrolled in Hedman et al. (2006)s' study. Assessed through the use of psychometric tests of Vanderberg and Kuse's mental rotation test (MRT) and Bas IQ among the participants, the study revealed that spatial ability among novice dental students was associated with skilled performance on a spatially complex surgical procedure. His findings also further confirmed that high levels of spatial ability could predict novice students' good academic performance in the early learning phases of visual-spatial complex tasks in key surgical activities. Suh and Cho (2020) investigated the relationship between spatial ability and design performance among novice students from an interior design program, using evaluations of a large-scale interior design project and scores on both a test of general spatial ability and a refined version of the architecture and interior design domain-specific spatial ability test. Their results showed that spatial ability positively correlated with creativity in the generation of three-dimensional volumetric design. They also examined whether students with high, medium, or low levels of spatial ability differing in the use of spatial strategies. Students with high spatial ability tended to show greater use of a generative approach in creating volumetric variations using complex axes, while those with medium and low spatial ability were inclined to add elements and details to simple volumes using relatively simple axes of 45°or 90°.

Academic performance in STEM or STEM-branch disciplines can be improved through even a short intervention based on spatially oriented activities. For example, Cheng and Mix (2014) carried out a study investigating whether spatial ability training improved mathematics performance among fifty-eight 6- to 8-year-old children. The experimental group received a single session of mental rotation training using an object completion task that had previously improved children's spatial ability in Ehrlich et al. (2006)' study, while the control group completed traditional crossword puzzles. The results of mathematics capacity pre- and post-test pointed out that children in the experimental group significantly improved in solving calculation problems, while children in the control group did not improve on any mathematics tasks. Furthermore, the results showed that the experimental group's improvement was largely due to better performance on missing term problems (e.g., 2+ = 9). Findings in this study showed a direct effect of spatial ability training on mathematics performance in early elementary-aged children.

These studies have evidenced that an individual's high level of psychometrically assessed spatial ability predicted good academic performance in computer programming (Jones and Burnett 2008), chemistry and physics learning (Kozhevnikov et al. 2007; Small and Morton 1983; Wu and Shah 2004), calculation problems (Cheng and Mix 2014), and even in complex surgical operations (Hedman et al. 2006; Roach et al. 2019) and architecture and interior design (Suh and Cho 2020). Furthermore, some research has established that spatial ability is malleable and that spatial ability responds positively to educational interventions (Buckley et al. 2018; Cheng and Mix 2014; Uttal et al. 2013). Consequently, spatial ability as a powerful systematic source of individual differences has increasingly received attention for its contribution to successful STEM education.

2.2 From Spatial Ability to Spatial Cognitive Process

Although there was certainty that spatial ability had positive educational effects in STEM education, prior studies did not offer a further explanation as to why spatial ability had such an effect on STEM education. Kirschner and van Merriënboer (2013) argued that 'research should not simply try to determine "what works" (cf. Chatterji 2004; Olson 2004) but should be aimed at explaining why particular methods help and why others do not help to reach particular goals in particular types of education under particular conditions'. Only when we understand the underlying mechanisms for this effect, will we be able to increase and optimise spatial ability' efficacy and related effects of teaching and learning for STEM education (Buckley et al. 2018). Therefore, there is now a need to explore this unknown topic i.e., the underlying spatial cognitive process (not observable) that is hidden within the spatial ability.

To represent the underlying spatial cognitive process that is hidden within spatial ability, earlier discussions of spatial ability have proposed substantial bottom-up conceptual frameworks of spatial factors for spatial ability through the use of traditional psychometrics and factor analysis. For example, Linn and Petersen (1985) proposed that spatial ability consisted of three spatial factors, spatial visualisation, mental rotation, spatial perception, while Carroll (1993) addressed a broad spectrum of five spatial factors, spatial visualisation, spatial relations (mental rotation as a subcomponent was involved in it), closure speed, flexibility of closure, and perceptual speed. Scholars did distinguish among various spatial factors, but they did so in a wide variety of ways that did not align well with each other (Newcombe and Shipley 2015; Buckley et al. 2018; Chen et al. 2020). Contention in these conceptual frameworks of spatial factors for spatial ability not only resulted in a vague theoretical foundation for revealing the nature of spatial ability but also affected the appropriateness of its measurement instruments. Buckley et al. (2018) cited Schneider and McGrew (2012)'s arguments denoting that almost all of the studies that showed spatial ability had predictive validity simply used spatial visualisation tests (or its subcomponent of mental rotation) as a proxy for spatial ability as a whole (e.g., methods in studies of Cheng and Mix 2014; Kozhevnikov et al. 2007; Jones and Burnett 2008; Roach et al. 2019).

Thus, scholars pointed out the use of bottom-up inductive approaches in traditional psychometrics and factor analysis to determine spatial cognitive process would be more difficult (Newcombe and Shipley 2015; Buckley et al. 2018; Chen et al. 2020), then put forward a claim that called for alternative paradigms coming from interdisciplinary fields (e.g., cognitive semantics, cognitive neuroscience) to support further inquiry into spatial ability and its underlying spatial cognitive process (Newcombe and Shipley 2015; Buckley et al. 2018; Wai et al. 2009). Some studies had launched this attempt. For example, based on Chatterjee (2008)'s study of spatial semantics and the previous literature reviewed, Newcombe and Shipley (2015) proposed a top-down conceptual framework of spatial factors for spatial ability. Spatial representations were divided into intrinsic or extrinsic, and spatial tasks were separated into static and dynamic forms. Then, a cross-tabulation matrix in spatial ability was developed: intrinsic-static (e.g., to identify objects as members of categories), intrinsic-dynamic (e.g., to imagine some future state of affairs), extrinsic-static (e.g., to represent spatial relationships among various objects in environments), and extrinsic-dynamic spatial cognitive factors (e.g., to maintain a representation of the world from different perspectives). However, they did not use this conceptual framework to empirically explain how these spatial factors come into effect and how to relate them to STEM education. Therefore, it is envisioned that other new top-down paradigms may become more appropriate in uncovering the underlying spatial cognitive process for spatial ability in the context of STEM education.

2.3 A Cognitive Neuroscience Approach to Explore Spatial Cognitive Process in the Context of STEM Education

Another area within spatial ability research where significant efforts have been made to uncover its full remit is the area of cognitive neuroscience. In recent years, cognitive neuroscience has been endeavouring to develop a cognitive map of the human mind (Sternberg 2000). Numerous implications extended from this, specifically within the context of STEM education, include the provision of a more top-down paradigm that could be used to aid in uncovering the roles of cognitive processes in STEM education (Buckley et al. 2018; Newcombe and Shipley 2015). Taking spatial cognition as an example, fields of cognitive neuroscience investigating spatial cognition not merely facilitated better understanding how students' spatial cognitive processes affect their STEM learning but also paved the way for the scientific refinement of spatial ability interventions and lateralisation of brain functions in STEM education (Buckley et al. 2018). Another example was addiction. Whether individuals were addicted to online video games or scientific inquiry, their addiction was related to the specific performance in the brain regions of the orbital frontal cortex (OFC) and anterior cingulate cortex (ACC), and to the variation of concentration of the neurotransmitter dopamine (Firth et al. 2019; Lubman et al. 2015; Ma et al. 2019; Quirino et al. 2019). Addiction could be promoted or hindered through these brain region-activated activities (Firth et al. 2019; Lubman et al. 2015). The connection between addiction and cognition would assist educators and practitioners to better understand students' adhesion to specific learning activities in the context of STEM education. Therefore, there is a great need to integrate cognitive neuroscience approaches with educational problems in STEM domains in the search of a new synthesis that offers meaning.

When tracing back to the development of the theoretical foundation of spatial cognition, it showed that how people processed spatial information to accurately navigate in real environments had been always a hot and productive research issue in research fields of spatial cognition. Human spatial navigation was closely related with two types of spatial-representational paths that intrinsically existed in human brains: navigation behaviour with external landmark (e.g., vestibular) cues (LM cues) and navigation behaviour with internal self-motion (e.g., proprioceptive) cues (SM cues) that signalled the organism's own movement. The former was associated with the activation of the medial temporal lobe (MTL) (Kessels et al. 2011). Individuals who were better at using external landmark cues had greater hippocampal volume in their brain structure (Maguire et al. 2000), and patients with hippocampal injury had difficulty navigating with external landmark cues (Astur et al. 2002). However, it was not sufficient to achieve accurate navigation by merely depending on external landmark cues (Nardini et al. 2008).

In recent years, a great breakthrough in spatial navigation pushed the development of human spatial cognition, uncovering a key mechanism underlying the cognitive process behind accurate spatial navigation. In 1970, John O’Keefe initially found that the neurons in the hippocampus demonstrated a specific performance when human spatial navigation functioned (O'Keefe and Dostrovsky 1971). In 2005, Edvard Moser and May-Britt Moser found that the neurons in the entorhinal cortex also displayed a specific performance when humans navigated to target objects. These two neurons were termed “place cells” and “grid cells”, respectively. The 2015 Nobel Prize for biology and medicine was awarded to the three scientists with outstanding contributions to the neural mechanisms of spatial navigation (Hafting et al. 2005; O'Keefe and Dostrovsky 1971). One of the important functions of grid cells is path integration (PI) (Gil et al. 2018; McNaughton et al. 2006). This ability to integrate paths is reflected in the use of internal self-motion cues for navigation. Their finding revealed that accurate navigation depended on the ability to integrate external landmark cues with internal self-motion cues rather than merely depended on either of the two types of spatial-representational paths (Gil et al. 2018; McNaughton et al. 2006). Nardini et al. (2008) further explored the development of path integration from children to adults (14 4- to 5-year-olds, 14 7- to 8-year-olds, and 17 adults with a mean age of 24.9). The results revealed that the children navigated the space merely depending on the alternative cue (i.e., LM cue or SM cue), whereas adults’ behaviour for navigating space was predicted by the cue integration model in which the LM and SM cues were weighted nearly optimally to reduce variance. The findings suggested that individuals’ higher capacity to integrate between LM and SM cues indicated higher levels of spatial ability. In other words, the spatial ability was malleable, reflecting promising potential for training and education (Uttal et al. 2013). Besides, spatial navigation was closely related to humans’ working memory capacity in the relevant hippocampal-entorhinal circuits (Buzsáki and Moser 2013) and even multiplexing neural mechanisms on a physiological basis (Battaglia et al. 2011). Therefore, theoretically speaking, studies on human spatial cognition in fields of cognitive neuroscience would provide a powerful means of investigating the role of spatial cognitive process in STEM education.

3 The Purpose of the Research

The literature reviewed here indicates that although the spatial ability gains a great focus in the context of STEM education, there is a further need to explain why spatial ability has such an effect in STEM education. As a result, scholars have claimed that students’ spatial cognitive process should be further explored through other new top-down paradigms due to technological limitations in traditional psychometrics and factor analysis. Moreover, the recent breakthrough of human accurate spatial navigation in the fields of cognitive neuroscience not only reveals the mechanism of spatial cognitive process but, more importantly, provide researchers with a powerful means to explore the relationship between spatial cognition and STEM education. Therefore, with the help of spatial navigation tests, the aim of this study is to explore the spatial cognitive process among STEM students and its role in STEM education. This study is therefore designed to address the following research questions that stem from the overall goal of this investigation:

1) What are the characteristics of spatial cognitive process among STEM students?
2) Is academic performance in STEM education associated with spatial cognitive process?
3) Are academic performances in the four branches of STEM education associated with a particular spatial cognitive process?

4 Methodology

4.1 The Participants

The aim of this study was to explore the spatial cognitive process among STEM education and its role in STEM education. The ideal candidates for this research are those: (a) who are from STEM or STEM-related majors, who are required to acquire and develop multidisciplinary knowledge and skills in the four branches of STEM education according to the new degree program issued by the Ministry of Education of China; (b) whose domain-specific knowledge and skills are under development and malleable rather than fixed. The second criterion was necessary to avoid good academic performance based on a great deal of semantic knowledge instead of reliance on their decontextualized spatial ability. Concerning the two criteria and to remove potential confounding factors such as domain-specific knowledge affected by non-spatial ability-related personal traits, novice students in the veterinary major were randomly selected from many STEM majors for this study.

A total of 194 Chinese second- and third-year students (mean age = 20.6 years, SD = 0.8; 48% males, 52% females) at a large comprehensive university in Hubei Province participated in this study. All the participants came from the veterinary major. In accordance with the Bachelor’s degree of Agronomy issued by the Ministry of Education of China and the veterinary talents training plan issued by their university, veterinary undergraduates were required to be well prepared with domain-specific knowledge and skills in science, technology, engineering, and mathematics during the 4 to 5 years of study. These undergraduates have just started their domain-specific leaning in the veterinary major, although they have learnt basic knowledge of mathematics, chemistry, and physics during the secondary phase of education. Prior to the study, all the students were informed of the main objective, procedures, and cautions in detail and gave informed consent to participate in this exploratory study. Besides, all the students were informed that they could quit this study at any time.

4.2 Spatial Navigation Test

According to the experimental design of human spatial navigation in Nardini et al.’s study (2008) (Fig. 1), a navigation behaviour test of a “homing task” was adopted and implemented in this study to explore spatial cognitive process among STEM students (Fig. 2). The test environment was equipped with a completely dark room, three different shapes of LED landmarks on the wall and three glowing toys on the floor (Fig. 1a). The completely dark room was an enclosed space (550 cm × 800 cm) (Fig. 1), surrounded by floor-to-ceiling shading curtains. The three LED landmarks (each was 30 cm × 15 cm) on the wall were in the shape of a star, a crescent, and lightning. The heights of the three LED landmarks from left to right were 50 cm, 150 cm, and 50 cm, and the horizontal interval was 150 cm (Fig. 1a). Three glowing toys were previously put on the ground (numbers 1 to 3 in Fig. 1), and the stable starting position for each student on each trial in the behaviour test of the “homing task” was also marked ("START" in Fig. 1), which was 275 cm away from the centre of the test field. While wearing sunglasses, the students only retained the visibility of the three LED landmarks on the wall and the three glowing toys on the ground, but could not distinguish the wall, ground, and ceiling (Figs. 1b and 2c). During the test, white noise was played from the loudspeaker above the centre of the field to mask the external sound and to reduce audio interference. In addition, a group of "conflict" landmarks was also prepared for further data analysis (Fig. 1c and Fig. 2d).

Each student was guided by the same voice guidance. On each trial, the student left the starting spot to pick up the three glowing toys on the floor in sequence and then attempted to return the first glowing toy to its original location. Students can relocate the position of the first glowing toy with the help of two types of spatial navigation cues: one is from the external visual cues of landmarks, and the other is from the internal non-visual cues of students' self-motion.

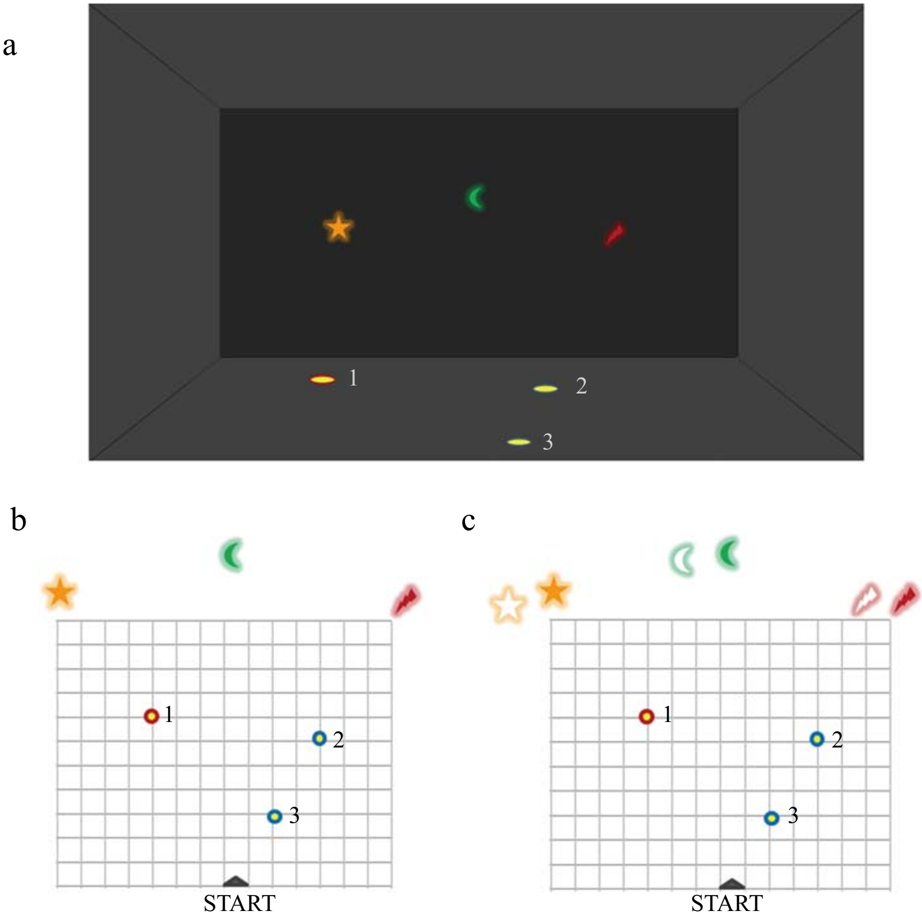

Fig. 1 The layout of spatial navigation test in Nardini et al.'s study (2008) **a**, **b** Scene of the layout of spatial navigation test from the top view in Nardini et al.'s study. In a completely dark room with three illuminated landmarks ("a star, a crescent, and a lightning") and three glowing toys, participants left the "START" position to collect the three glowing toys on the floor in sequence (1, 2, 3), then attempted to return the first glowing toy to its original location. **c** Scene of added "conflict" landmarks from the top view

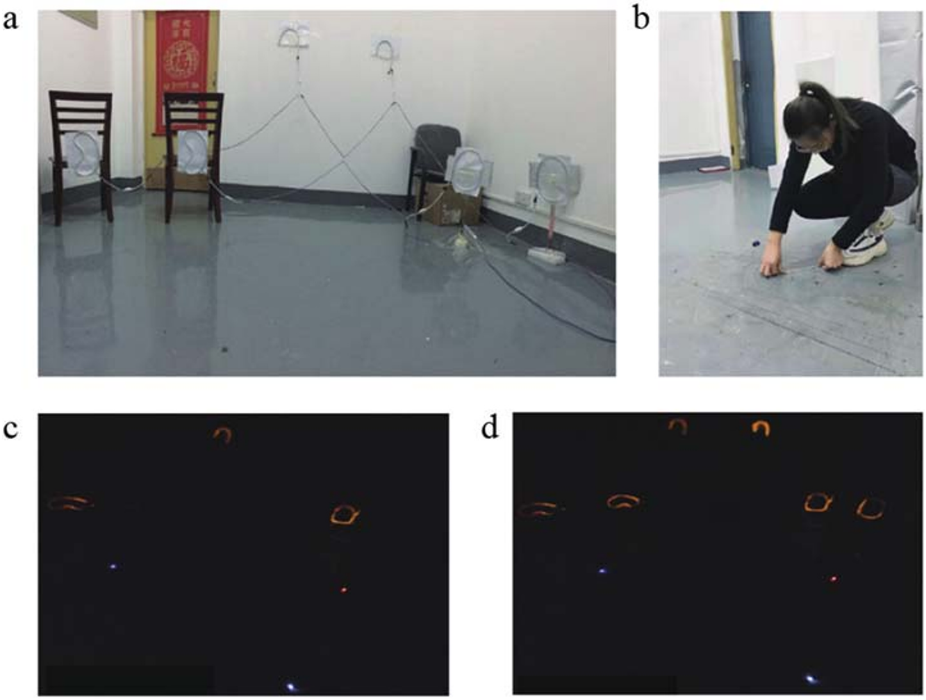

Fig. 2 The layout of spatial navigation test and scenes of test conditions in the present study **a** Scene of the layout of spatial navigation test from the front view in the present study. **b** Measuring the error distance (cm) and deviation angles (°) between students' responses and the original location of the first glowing toy. **c** Scene of landmarks condition (LM) from the students' view. **d** Scene of added "conflict" landmarks.

We implemented the homing task under three differing conditions (Fig. 3). The first test condition was self-motion condition (SM). In SM, students' relocation of the first glowing toy only could depend on non-visual self-motion cue when the landmarks were switched off and the room was left in complete darkness. The second test condition was landmark condition (LM). In LM, the landmarks remained visible, but students were disoriented by turning; hence, students only relied on external visual landmark cues for navigation and relocation. The third test condition was self-motion and landmark condition (SM + LM). In SM + LM, both cues were available, as students remained oriented and landmarks remained visible. Each student repeated the homing task four times under each condition.

4.3 Data Collection

4.3.1 The Data of Spatial Navigation Behaviours

All the students successfully completed the homing task under the three conditions without termination. On each trial for each student, we recorded the error distance (cm) and deviation angles (°) between her or his response and the correct location. In addition, we added a group of conflict landmarks that consisted of a duplicate of each landmark. The group of conflict landmarks was rotated by 15° about the centre of the test field (Figs. 1c and 2d), which was used to test the weight value of students' adoption of external landmark cues.

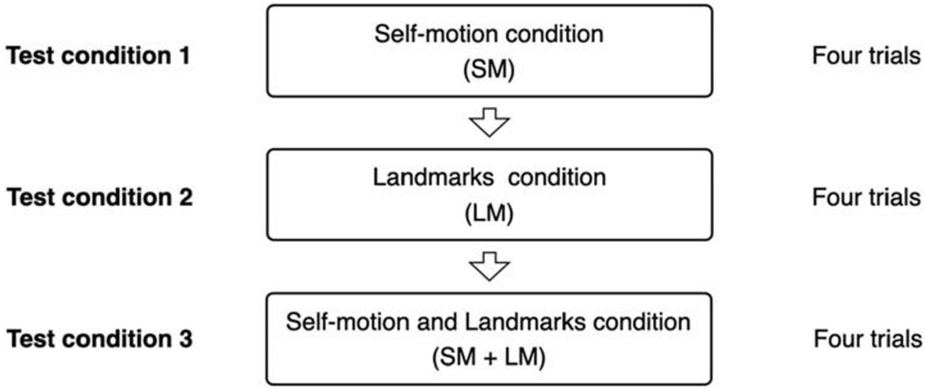

Fig. 3 The procedure of spatial navigation test in the present study

4.3.2 The Data of Academic Performance in STEM Education

The data of academic performance in STEM education were from academic scores of four subjects in the final exam of the fall semester of 2019, which were selected to stand for the four branches of STEM education. Advanced Mathematics represented Mathematics, Inorganic and Analytical Chemistry represented Science, and Computer basics represented Engineering. In accordance with the actual curriculum design of Animal Physiology, veterinary students should acquire a substantial amount of declarative and procedural knowledge on biochemistry technology and hands-on operation of experiments in the course of Animal Physiology, such as a deep understanding of the history of biochemistry technology development, utilising the technology of polymerase chain reaction (PCR) to detect animal genetic disease and adopting enzyme-linked immunosorbent assay (ELISA) to achieve an accurate diagnosis of animal infectious pathogens. Therefore, academic scores in Animal Physiology were selected to be representative of academic performance in the "T" branch of STEM education.

4.4 Data Analysis

First, we analysed two types of spatial navigation error sources: constant error and variable error. Constant error, such as a tendency to overshoot or undershoot, was the actual location deviation of the absolute value size by calculating the real error of the root mean square error (RMSEs) under each condition. The variable error referred to the dispersion of responses by analysing standard deviations (SDs) of responses (i.e., the dispersion of each student's responses about their own mean response location in repeated times).

Second, based on the aforementioned analysis, the two models of spatial cognitive process in the utilisation of internal self-motion and external landmark cues were further developed. One was a cue integration model, which made comprehensive use of internal SM and external LM cues, gave different weights to different types of cues, and finally obtained the final decision mode after weighted sum. The other was the cue-alternation model, which did not integrate internal self-motion with external landmark cues but selected one of them as the decision basis with a certain probability under the repeated trials. In the process of variable error analysis, for the cue integration model, the predicted variable errors σ^2_{SM+LM} came from the weighted sum of internal SM and external LM cues:

$$\sigma^2_{SM+LM} = w^2_{SM}\sigma^2_{SM} + w^2_{LM}\sigma^2_{LM} \tag{1}$$

the weight of which was normalised: ($w_{LM} = 1 - w_{SM}$).

For the cue-alternation model, the predicted variable errors came from the mixed distribution of variable errors when the single navigation cue was used solely. Assuming that the response distribution when SM or LM cues were used solely had the variance SM and LM, and the mean kept SM and LM. The variable errors in the mixed distribution were shown in Eq. 2, where p_{SM} and p_{LM} were the probability of choosing two types of navigation cues (normalization) with SM = 0 and LM = 46 cm (due to the conflicting condition, the measured moving distance of the landmark after rotation of 15°was 46 cm):

$$\sigma^2_{SM+LM} = p_{SM}\left(\mu^2_{SM} + \sigma^2_{SM}\right) + p_{LM}\left(\mu^2_{LM} + \sigma^2_{LM}\right) - \left(p_{SM}\mu_{SM} + p_{LM}\mu_{LM}\right)^2 \tag{2}$$

Third, to explore the association between students' spatial cognitive process and academic performance in STEM education, we sorted the students according to individual total scores in STEM education (i.e., summing up academic scores in the four branches of STEM), ranking the first 1/3 as the high score group and the last 1/3 as the low score group. We then compared root mean square errors (RMSEs) and standard deviations (SDs) among the two groups. In this step, the data of 22 students were ruled out due to their default of academic scores in the final exam.

Finally, to confirm whether academic performances in the four branches of STEM education are associated with a particular spatial cognitive process, this study further explored students' strategic utilisation of internal self-motion and external landmark cues in each branch of STEM. According to individuals' academic scores in each branch of STEM (i.e., Science, Technology, Engineering, and Mathematics), the first 1/3 of the ranking in each branch of STEM was divided into the high score group and the last third into the low score group. We examined the relationship between the behaviours in the single cue state, integration cue state, and their academic scores in each branch of STEM among the two groups. All data processing and statistical analyses were performed using MATLAB 2018b (Mathworks Inc., USA).

5 Results

5.1 Spatial Cognitive Process Among STEM Students in STEM Education Featured Cue Integration

Depending on the cognitive neuroscience approach of spatial navigation test, we first investigated the characteristics of spatial cognitive process among STEM students. The results are presented in Fig. 4.

Regarding constant error (i.e., RMSE) under LM, SM, and LM + SM states, students' navigation behaviours under LM state were significantly better than those under SM state (t (384) = 2.62, $p < .001$), and students' navigation behaviours with the use of both external landmarks and internal self-motion cues were significantly better than their navigation behaviours with the use of any single navigation cue (t (384) = 2.65, $p < .001$ (Fig. 4a).

Regarding variable errors (i.e., SD), there was no significant difference when the single navigation cue was used, and only when two types of navigation cues were used in combination could the variable errors be significantly reduced (t (384) = 2.69, $p < .001$) (Fig. 4b).

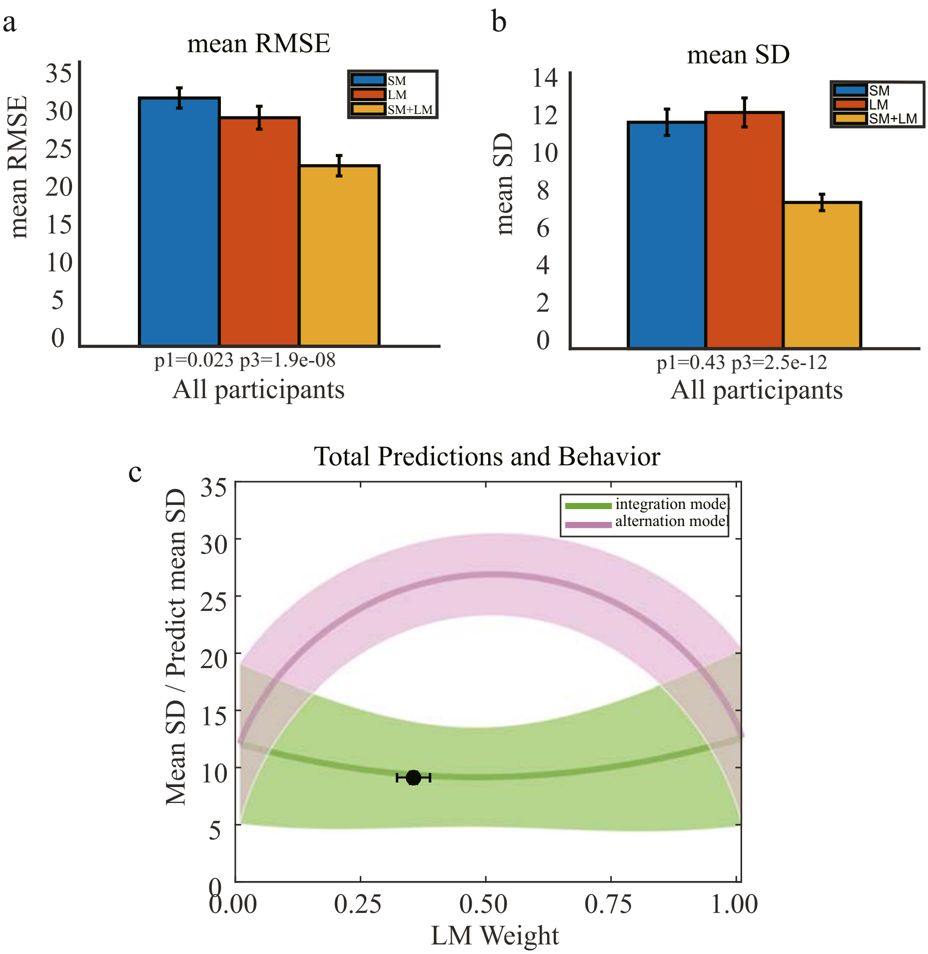

Fig. 4 Characteristics of spatial cognitive process among STEM students. **c** The green and red curves depicted the means of functions, predicting mean standard deviation (SDs) from different landmarks weights (cue integration model) or landmarks probabilities (cue alternation model), respectively. The *X*-axis showed an increasing reliance on landmarks from left to right. The black points plot measured the position of the average SDs and the average relative landmarks dependence degree, and the black points plot in this result fell within the curve range of the cue integration model

Regarding behaviour prediction under the conflict condition, the green and red curves depicted the mean value of the function predicting mean SDs with different landmark weights (cue integration model) or cue selection probabilities (cue-alternation model), respectively. The X-axis showed an increasing reliance on landmarks from left to right. The data point plot measured the position of the average SDs and the average relative landmark dependence degree, and the data points in the plot fell within the curve range of the integrated model. The results showed that comparing the cue integration model with the cue-alternation model, the students' utilisation of navigation cues was consistent with the cue integration model (Fig. 4c), revealing that the developmental state of students' spatial cognitive process in this study echoed the previous findings (Nardini et al. 2008): the data points fell on the curve of the cue integration model. According to Nardini et al.'s study, the data points fell on the curve of the cue-alternation model during the developmental state of spatial cognitive process among the children, while for the adults, the data points fell on the curve of cue integration. These results indicated that STEM students had developed mature adults' spatial cognitive process, featuring the integration of internal self-motion and external landmark cues, which has thus been prepared with the essential spatial cognitive requirements in respect of successful STEM learning.

5.2 Students with Higher Levels of Cue Integration Indicated Their Better Academic Performance in STEM Education

To uncover the association between students' spatial cognitive process and academic performance in STEM education, we examined whether students in the high and low score groups differed in levels of cue integration. The results showed that the constant error (Fig. 5a) and variable error (Fig. 5b) in the high score group were significantly lower than those in the low

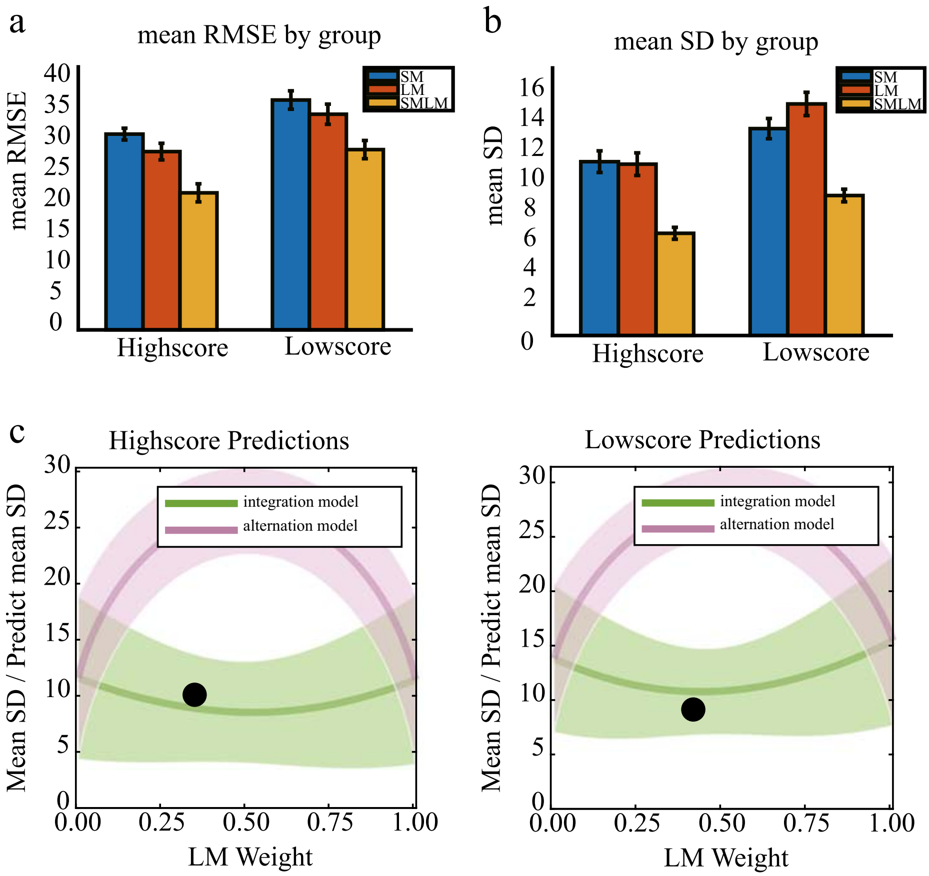

Fig. 5 Comparing the levels of cue integration between the high and low score groups of academic performance in STEM education (**c**) The green and red curves depicted the means of functions, predicting mean standard deviation (SDs) from different landmarks weights (cue integration model) or landmarks probabilities (cue alternation model), respectively. The X-axis showed an increasing reliance on landmarks from left to right. The black points plot measured the position of the average SDs and the average relative landmarks dependence degree, and the black points plot in this result fell within the curve range of the cue integration model.

score group (t (106) = 2.71, $p < .001$; t (106) = 2.69, $p < .001$), although within each group, students' navigation behaviours with the use of both cues were better than their navigation behaviours with the use of any single navigation cue. In addition, the navigation behaviours in both groups also confirmed the prediction of the cue integration model (Fig. 5c). These results revealed that the capacity to integrate internal self-motion and external landmark navigation cues was positively correlated with academic performance in STEM education. In other words, students' better ability to integrate navigation cues indicated better academic performance in STEM education.

5.3 Academic Performances in Each Branch of STEM Education Relied on Students' Particular Spatial Cognitive Process

To further refine the association between spatial cognitive process and academic performance in each branch of STEM education, this study further explored students' strategic utilisation of internal self-motion and external landmark cues on the specific STEM subjects. The results showed that, interestingly, students with high scores in science and mathematics were more inclined to reduce cognitive behavioural constant errors through depending on their internal SM cues (science: t (106) = 2.7, $p < .001$; mathematics: t (106) = 2.82, $p < .001$) (left column of Fig. 6a), while students with high scores in technology and engineering were more inclined reduce both constant and variable errors of cognitive behaviours through depending on their external LM cues (the constant errors of cognitive behaviours for technology: t (106) = 2.89, $p < .001$, and for engineering: t (106) = 2.68, $p < .001$ (middle column of Fig. 6a); the variable errors of cognitive behaviours for technology: t (106) = 2.91, $p < .001$, and for engineering: t (106) = 2.75, $p < .001$) (middle column of Fig. 6b)). The results demonstrated that science and mathematics relied more on the students' ability to use self-motion internal cues, and technology and engineering subjects were more dependent on the guidance of external landmark cues, although successful learning in all four branches of STEM education required the high levels of cue integration.

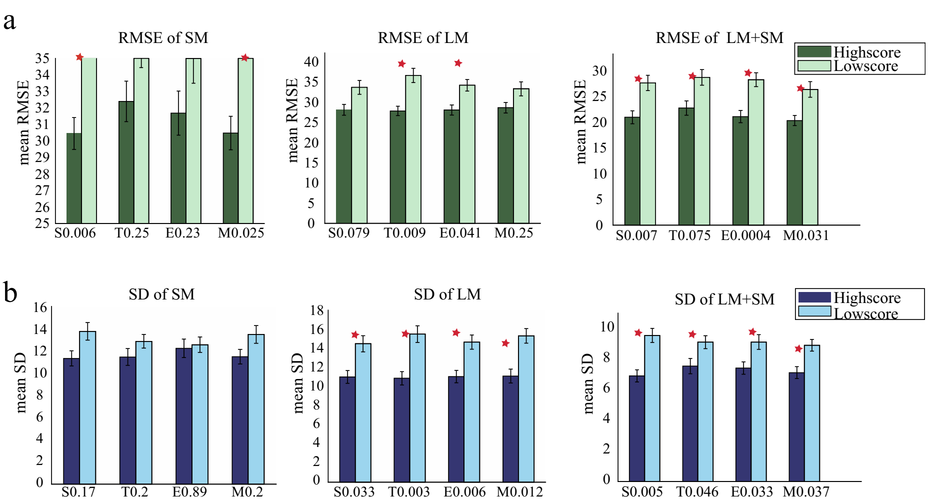

Fig. 6 Comparing the dependence degree of two types of navigation cues between high score and low score groups of academic performance in each branch of STEM education. The letters on the X-axis: S science, T technology, E engineering, M mathematics. The red star indicated $p < 0.05$.

6 Discussion and Implications

Depending on the cognitive neuroscience approach of the spatial navigation test, we attempted to explore the spatial cognitive process among STEM students and its role in STEM education. The students that we randomly selected were from a specific age group (undergraduates), in a specific major (veterinary), and in a specific country (China), who were usually considered novice students in STEM domains (Uttal and Cohen 2012). In contrast to professional experts in STEM domains, previous studies have suggested that novice students tend to rely more on decontextualised spatial ability rather than a great deal of semantic knowledge to solve a substantial number of tasks with spatial nature in STEM domains. Due to that consideration, participants enrolled in this study were appropriate to respond to the series of three research questions.

The first research question concerned the characteristics of spatial cognitive process among STEM students. Through utilising a bottom-up inductive approach of the kind used in traditional psychometric and factor analysis, prior research could not depict a clear theoretical picture of spatial ability and its underlying spatial cognitive process (Buckley et al. 2018; Newcombe and Shipley 2015; Uttal and Cohen 2012). Luckily, studies on spatial cognitive process in the fields of cognitive neuroscience not only offered an up-down theoretical paradigm but also provided a powerful means to reinvestigate spatial ability and to uncover the role of underlying spatial cognitive process in the context of STEM education (Battaglia et al. 2011; Bellmund et al. 2018; Buzsáki and Moser 2013; Hafting et al. 2005). Therefore, with the help of the cognitive neuroscience approach, this study analysed and modelled 197 participants' navigation behaviours in a spatial navigation test named "homing task". The results showed that spatial cognitive processes among STEM students were explicitly featured with cue integration. Behind cue integration was neural mechanisms in relevant brain regions. The use of external landmark cues involved the activities of the medial temporal lobe (MTL) (Kessels et al. 2011), while the use of internal self-motion cues involved entorhinal cortex path integration mechanisms (Battaglia et al. 2011; Buzsáki and Moser 2013). Cue integration should enable more accurate localization in the real-world settings than depending on either external landmark cues only or internal self-motion cues only, since in the spatial cognitive process of cue integration the external landmark and internal self-motion cues were weighted nearly optimally to reduce behaviour variance (Battaglia et al. 2011; Buzsáki and Moser 2013). Nardini et al. (2008)'s study focused on the development of cue integration in human navigation, revealing that the children navigated the space only depending on the alternative cue (i.e., either external landmark or internal self-motion cues), whereas the adults' behaviour for navigating space was predicted by the cue integration model. The present findings added to Nardini et al. (2008)'s study showed the spatial cognitive process of cue integration existing, not only among adults who had been working for years but also saliently among the group of novice students in STEM domains.

In China, students who wanted to go on to advanced educational stages in STEM majors were required to pass the National College Entrance Examination (NCEE) with higher scores in mathematics and multiple disciplines of science (including physics, chemistry, and biology) than those desiring non-STEM majors (Jiachen 2019). Therefore, this finding also indicated that NCEE could to some extent identify talents that have been prepared with the essential spatial cognitive requirements for STEM learning and development. Future research could explore whether spatial cognitive process of cue integration would be a requisite gateway to achieve advanced educational and occupational credentials in STEM.

The second research question asked: “Whether academic performance in STEM education is associated with spatial cognitive process?” This finding presented here showed that students who have higher levels of integrating the internal self-motion and external landmark cues indicated a better overall academic performance in STEM education. This finding corroborated prior findings on the close relationship between students’ spatial ability and academic performance in STEM or STEM-branch disciplines (Buckley et al. 2018; Cheng and Mix 2014; Jones and Burnett 2008; Kozhevnikov et al. 2007; Marunic and Glazar 2013; Newcombe 2017; Pittalis and Christou 2010; Roach et al. 2019; Small and Morton 1983; Wai et al. 2009; Wu and Shah 2004) and go further in explaining why spatial ability had such a significant impact on STEM educational achievement from the neuroscience cognitive perspective. The spatial cognitive process of cue integration that was hidden within spatial ability offered strong support for accomplishing complex spatial tasks in the real-world settings as well as in the context of STEM education including intertwined relationships of objects, different perspective-taking frames (e.g., I-you, here-there, and now-then), and more than one possible path or solution (Nardini et al. 2008). Students with high levels of cue integration not only had high commitment to seek the relationships and interactions between new and existing concepts and propositions but would also synthesise more effective ways of thinking from among the existing possibilities, which resulted in meaningful learning, and in turn, led to increased academic performance in STEM and increased motivation to learn STEM (Novak 2002).

The third research question addressed and refined students’ spatial cognitive processes in each branch of STEM education, i.e., whether academic performances in the four branches of STEM education are associated with particular spatial cognitive processes. This finding demonstrated that, surprisingly, better academic performances in science and mathematics relied more on the students’ strategic utilisation of internal self-motion cues, while better academic performances in technology and engineering were more dependent on the guidance of external landmark cues, even though successful learning in each branch of STEM education required students to better integrate both navigation cues. This was the first study demonstrating differences in students’ spatial cognitive processes in different branches of STEM education, even though the tasks to be solved in all four branches of STEM education were all thought to be highly dependent on spatial ability. We offered one potential explanation: on the one hand, goals of science/mathematics education often included an emphasis on considering multiple possible explanations in terms of a specific natural phenomenon and an emphasis on the revision of science explanations after verifying and arguing initial claims (NRC 2012).

Historical discoveries and theoretical growth of content knowledge in science and mathematics were always intertwined with scientists or mathematicians’ self-awareness of ways of thinking inspired by seemingly irrelevant events, and therefore, better academic performance in science and mathematics was naturally and closely related with the better utilisation of internal self-motion cues. For example, Kekule’s dream of snakes biting each other’s tails inspired his discovery of the structure of the benzene ring (Newcombe 2017). Another example was that Alfred Wegener presented *continental drift theory*. He first thought of the continental drift hypothesis by noticing that the different large landmasses of the Earth almost fitted together similar to a jigsaw puzzle. It was the jigsaw puzzle-like landmasses of the Earth that inspired him to raise research ideas and guided him to verify this hypothesis through many repeated experiments and scientific arguments with his colleagues (Romano et al. 2017). On the other hand, inventions in fields of technologies and engineering of a design nature had their roots in simulation in the real world (Magana 2017; Xie et al. 2018). Therefore, good academic performance in technology and engineering is closely related to the optimal simulation of natural objects through relying on subtle observation and analysis of their visual external features (Magana 2017; Xie et al. 2018). For example, the Wright brothers observed and concluded that birds changed the angle of the ends of their wings to make their bodies roll right or left. The brothers then decided this would also be a good way for a flying machine to turn to "bank" or "lean", similar to a bird (Howard 2013; Jakab 2014).

All in all, while this study confirmed again that spatial ability played a critical role in STEM education from the perspective of cognitive neuroscience, we did not feel that spatial ability should be used as a means of predetermining STEM aptitude. Since substantial research had established that spatial cognition was malleable (Nardini et al. 2008), individuals' spatial ability should be trained and improved while tailoring pedagogical interventions and refining procedures on the basis of individual differences in spatial cognitive process (Buckley et al. 2018). Consideration needs to be given to STEM learning design, including curriculum design, learning activities design, and even learning tools and environments design, that helps students with low spatial ability or STEM low-achievers to synthesise the spatial cognitive process of cue integration into their mental schema to extend spatial ability and build better mental schema of STEM learning (Jones and Burnett 2008; Wiedenbeck et al. 2004).

Therefore, implications for STEM learning design and STEM teaching should be further outlined and discussed. Based on the findings in research questions, STEM learning design and STEM teaching should be led by three concerns for supporting STEM students' development of spatial cognitive process i.e., "what could be referred to as external landmark cues and how to facilitate the use of external landmark cues in the context of STEM education?", "what could be referred to as internal self-motion cues and how to facilitate the use of internal self-motion cues in the context of STEM education?" and "how to facilitate the integration of both of the above navigation cues in the context of STEM education?"

Concerning what could be referred to as external landmark cues and how to facilitate the use of external landmark cues in the context of STEM education, external landmark cues in the context of STEM education could refer to a substantial number of visual, explicit prompts, hints, or guidance existing in physical space (e.g., STEM curriculum, learning materials, and learning environments). Sometimes these hints aimed to illustrate the learning objectives or models of the design processes in STEM curriculum. For example, the design was the core problem-solving process of both engineering and technological education (ITEEA 2007). In the practice of engineering and technology, based on the consideration of model structure adequacy (Taper et al. 2008), students should be provided with more opportunities to select a fit model of design process to resolve the engineering and/or technological problems. It would support students with clear guidance in the different iterative phases of design process. For example, most models of the engineering design process included formulating an explicit problem by identifying criteria and constraints for available solutions, creating a number of possible solutions, evaluating the solutions to determine which solution best suited for the problem requirements, and optimising the solution by verifying and redesigning (ITEA 2000; Lucas and Hanson 2016; Moore et al. 2014; NRC 2010).

Sometimes, these hints could reflect the rightness or wrongness of conceptual understandings. For example, scholars have demonstrated that replacing a standard expository text with a refutation text with directly referred to common misconceptions, refuting and contrasting them with the correct explanations significantly fosters students' conceptual understanding of complex and counterintuitive knowledge systems in textbooks (Asterhan and Resnick 2020; Braasch et al. 2013; Danielson et al. 2016; Mason et al. 2017). Besides, instructions that aimed to explicitly reveal the relationships among different dimensions of science ideas might also be viewed as a type of external landmark cues in a broad sense. For example, to help students make sense of phenomena and clearly explain why and how phenomena occur, Krajcik (2015) proposed a new type of teaching, *Three-Dimensional Instruction*. Students were encouraged in the science classrooms to explore, examine, and use the three-dimensional science ideas of disciplinary core idea, scientific and engineering practices, and crosscutting concepts (NGSS 2013; NRC 2012) to build models, design investigations, share ideas, develop explanations, and argue using evidence. As students grappled with making sense of phenomena, they would build a deeper understanding of science itself rather than science content (Connolly 2019; Krajcik 2015; Shin et al. 2019). Therefore, STEM learning design and STEM teaching, especially for engineering and technology, should highlight the utility of explicit guidance to improve students' perception and use of external landmark cues in STEM learning.

When concerning what could be referred to as internal self-motion cues in the context of STEM education and how to facilitate the use of internal landmark cues in the context of STEM education, internal landmark cues in the context of STEM education were nonvisual self-generated and implicit. They focused on what ways of thinking might advance a better understanding of the whole system. The use of internal self-motion cues not only reflected ways of thinking but also synthesised a point of view from different perspectives. Therefore, learning activities, especially for mathematics and science, should focus on how to trigger students' self-awareness of their internal ways of thinking, the ways of organising ideas, and the ways of interacting with others' thinking. For example, scientific argumentation in collaborative groups as a practice under the umbrella of scientific inquiry could create an argumentative space for students to interpret their own claims (or ideas), externalise their processes of reasoning, and be exposed to others' thinking. Many different claims (or ideas) would be verified, weighed, restructured, and, at times, abandoned (Archila et al. 2020; Asterhan and Resnick 2020; Evagorou and Osborne 2013; Heng et al. 2015; Pabuccu and Erduran 2017; Sampson and Clark 2009). Through this way, students would have a better understanding of how scientists and their science communities discovered and explained natural phenomena and how knowledge and theories were generated, verified, developed, or abandoned.

When concerning how to facilitate the integration of both navigation cues in the context of STEM education, the integration among various learning materials and learning activities should be further explored. For example, Asterhan and Resnick (2020) stated that a future study should explore how effects of scientific argumentation may be augmented with refutation texts in science education since refutation text reading and scientific argumentation in collaborative groups were expected to complement each other by supporting the use of both of the above navigation cues. In addition, learning tools should also be tailored to fit the needs of explicitly external guidance and externalised self-perception in STEM classrooms, such as cognitive tools (e.g., concept mapping (Hwang et al. 2013)) and navigation tools (McMahon et al. 2015).

7 Conclusion

This study combined the cutting-edge achievements of cognitive neuroscience fields and educational problems in the domains of STEM education to explore the role of spatial cognitive process in STEM education. The findings revealed that the integration of internal self-motion and external landmark cues was the key to the effectiveness of STEM learning through modelling analysis of navigation behaviours among large-scale veterinary students. Students with high levels of cue integration outperformed in STEM learning. Furthermore, the findings also revealed that good academic performance in the four branches of STEM education relied on different spatial cognitive processes. Specifically, internal self-motion cues were of greater significance to science and mathematics learning, while engineering and technology learning laid more emphasis on the effective use of external guidance cues.

Prior to this study, interdisciplinary explorations on spatial cognitive process in the context of STEM education, especially those based on cognitive neuroscience approaches, were very scarce. Studies on cognitions (not merely for spatial cognition) could provide a top-down research paradigm to facilitate investigating the roles of many cognitive processes in STEM education and a better understanding of the reason why a specific ability had such an impact in STEM education. When we understood their underlying mechanism, we could scientifically refine and optimise the efficacy of cognitive interventions and by association, STEM education practice to provide better support for STEM learning and STEM low-achievers.

8 Limitations and Future Research

First, this study was limited in that the findings presented here were obtained from a specific subject group (novices) in a specific STEM major (veterinary) from a specific country (China). When evaluating the results of this study, one must be mindful that different subject groups, such as professional veterinarians or novices from other STEM majors, would have affected the results differently. Second, even though the sample was sufficiently large, the data of 22 students were ruled out when they responded to the second and third research questions because their academic scores were valued as default. This issue has been reported in several educational studies (Lin et al. 2020). Even so, it was difficult to address this problem.

Third, only behaviour tests were implemented in this study. Future studies should value the role of important real-time physiological indexes of neuroscience cognitive competence, together with MEG (magnetoencephalography), EEG (electroencephalogram), and fMRI (functional magnetic resonance imaging), and fNIRS (functional near-infrared spectroscopy). Depending on the above approaches in the fields of cognitive neuroscience, it was promising to measure the relevant neural circuits in the functions of STEM-relevant connections in the brains of the different phases of STEM education and biomarkers, thus providing deep implications to learning design, STEM teaching, STEM assessment, and STEM talent identification. Each link would be supported by scientific and effective cognitive mechanisms. Also, to understand more comprehensive aspects of spatial ability and academic performance, empirical studies should further explore the potential relationships between the other cognitive capacities and students' spatial performance, the role of students' spatial cognitive process in their specific skills or performance (e.g., surgical skills or clinical reasoning skills), and the differences of spatial cognitive process among the different subject groups (e.g., male and female, STEM students, and non-STEM students) through including extensive triangulation with students' self-report and interview data on the spatial strategies used.

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Data Availability The data and material used in the paper is available from the authors upon request.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest

Ethics Approval This study has gained the approval from the ethical committee of the Faculty of Education at Beijing Normal University.

Code Availability The code used in the paper is available from the authors upon request.

References

Archila, P. A., Molina, J., & de Mejía, A. M. T. (2020). Using historical scientific controversies to promote undergraduates' argumentation. *Science & Education*. https://doi.org/10.1007/s11191-020-00126-6.

Asterhan, C. S., & Resnick, M. S. (2020). Refutation texts and argumentation for conceptual change: a winning or a redundant combination? *Learning and Instruction, 65*, 101265.

Astur, R. S., Taylor, L. B., Mamelak, A. N., Philpott, L., & Sutherland, R. J. (2002). Humans with hippocampus damage display severe spatial memory impairments in a virtual Morris water task. *Behavioural Brain Research, 132*(1), 77–84.

Battaglia, F. P., Benchenane, K., Sirota, A., Pennartz, C. M., & Wiener, S. I. (2011). The hippocampus: hub of brain network communication for memory. *Trends in Cognitive Sciences, 15*(7), 310–318.

Belland, B. R., Walker, A. E., Kim, N. J., & Lefler, M. (2017). Synthesizing results from empirical research on computer-based scaffolding in STEM education: a meta-analysis. *Review of Educational Research, 87*(2), 309–344. https://doi.org/10.3102/0034654316670999.

Bellmund, J. L., Gärdenfors, P., Moser, E. I., & Doeller, C. F. (2018). Navigating cognition: spatial codes for human thinking. *Science, 362*(6415), eaat6766. https://doi.org/10.1126/science.aat6766.

Braasch, J. L., Goldman, S. R., & Wiley, J. (2013). The influences of text and reader characteristics on learning from refutations in science texts. *Journal of Educational Psychology, 105*(3), 561. https://doi.org/10.1037/a0032627.

Buckley, J., Seery, N., & Canty, D. (2018). A heuristic framework of spatial ability: a review and synthesis of spatial factor literature to support its translation into STEM education. *Educational Psychology Review, 30*(3), 947–972. https://doi.org/10.1007/s10648-018-9432-z.

Buzsáki, G., & Moser, E. I. (2013). Memory, navigation and theta rhythm in the hippocampal-entorhinal system. *Nature Neuroscience, 16*(2), 130. https://doi.org/10.1038/nn.3304.

Carroll, J. B. (1993). *Human cognitive abilities: a survey of factor-analytic studies*. Cambridge University Press.

Chatterjee, A. (2008, August). The neural organization of spatial thought and language. *In Seminars in speech and language* (*Vol. 29*, no. 03, pp. 226-238). © Thieme Medical Publishers.

Chatterji, M. (2004). Evidence on "what works": an argument for extended-term mixed-method (ETMM) evaluation designs. *Educational Researcher, 33*(9), 3–13. https://doi.org/10.3102/0013189X033009003.

Chen, Y. C., Yang, F. Y., & Chang, C. C. (2020). Conceptualizing spatial abilities and their relation to science learning from a cognitive perspective. *Journal of Baltic Science Education, 19*(1), 50–63. https://doi.org/10.33225/jbse/20.19.50.

Cheng, Y. L., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development, 15*(1), 2–11. https://doi.org/10.1080/15248372.2012.725186.

Connolly, R. B. (2019). Teachers' understanding and usage of scientific data visualizations for teaching topics in earth and space science (Doctoral dissertation, Columbia University).

Danielson, R. W., Sinatra, G. M., & Kendeou, P. (2016). Augmenting the refutation text effect with analogies and graphics. *Discourse Processes, 53*(5–6), 392–414. https://doi.org/10.1080/0163853X.2016.1166334.

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology, 42*(6), 1259. https://doi.org/10.1037/0012-1649.42.6.1259.

Ertl, B., Luttenberger, S., & Paechter, M. (2017). The impact of gender stereotypes on the self-concept of female students in STEM subjects with an under-representation of females. *Frontiers in Psychology, 8*, 703. https://doi.org/10.3389/fpsyg.2017.00703.

Evagorou, M., & Osborne, J. (2013). Exploring young students' collaborative argumentation within a socioscientific issue. *Journal of Research in Science Teaching, 50*(2), 209–237. https://doi.org/10.1002/tea.21076.

Firth, J., Torous, J., Stubbs, B., Firth, J. A., Steiner, G. Z., Smith, L., et al. (2019). The "online brain": how the Internet may be changing our cognition. *World Psychiatry, 18*(2), 119–129.

Gil, M., Ancau, M., Schlesiger, M. I., Neitz, A., Allen, K., De Marco, R. J., & Monyer, H. (2018). Impaired path integration in mice with disrupted grid cell firing. *Nature Neuroscience, 21*(1), 81–91.

González-Howard, M. (2019). Exploring the utility of social network analysis for visualizing interactions during argumentation discussions. *Science Education, 103*(3), 503–528. https://doi.org/10.1002/sce.21505.

Hafting, T., Fyhn, M., Molden, S., Moser, M. B., & Moser, E. I. (2005). Microstructure of a spatial map in the entorhinal cortex. *Nature, 436*(7052), 801–806. https://doi.org/10.1038/nature03721.

Hedman, L., Ström, P., Andersson, P., et al. (2006). High-level visual-spatial ability for novices correlates with performance in a visual-spatial complex surgical simulator task. *Surgical Endoscopy, 20*, 1275–1280.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34*(2), 151–176.

Heng, L. L., Surif, J., & Seng, C. H. (2015). Malaysian students' scientific argumentation: do groups perform better than individuals? *International Journal of Science Education, 37*(3), 505–528.

Howard, F. (2013). *Wilbur and Orville: a biography of the Wright brothers*. Courier Corporation.

Hwang, G. J., Yang, L. H., & Wang, S. Y. (2013). A concept map-embedded educational computer game for improving students' learning performance in natural science courses. *Computers & Education, 69*, 121–130. https://doi.org/10.1016/j.compedu.2013.07.008.

International Technology and Engineering Educators Association (ITEEA). (2007). *Standards for techno logical literacy: content for the study of technology*. International Technology and Engineering Educators Association (ITEEA): Reston.

International Technology Education Association. (2000). *Standards for technological literacy*. Reston: International Technology Education Association.

Jakab, P. L. (2014). Visions of a flying machine: the Wright brothers and the process of invention. Smithsonian Institution.

Jiachen, L (2019). 高考改革对清华本科生 STEM 学业成绩的影响[An empirical study of the influence of college entrance examination reform on stem academic achievements of undergraduate students in Tsinghua university].*Research in Higher Education of Engineering, 4*,152–158.

Jones, S., & Burnett, G. (2008). Spatial ability and learning to program. Human Technology*:* An Interdisciplinary Journal on Humans in ICT Environments. http://urn.fi/URN:NBNfi:jyu-200804151352. Accessed 6 April 2020.

Kessels, R. P., Van Doormaal, A., & Janzen, G. (2011). Landmark recognition in Alzheimer's dementia: spared implicit memory for objects relevant for navigation. *PLoS One, 6*(4), e18611.

Kirschner, P. A., & van Merriënboer, J. J. (2013). Do learners really know best? Urban legends in education. *Educational Psychologist, 48*(3), 169–183. https://doi.org/10.1080/00461520.2013.804395.

Kozhevnikov, M., Motes, M. A., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science, 31*(4), 549–579. https://doi.org/10.1080/15326900701399897.

Krajcik, J. (2015). Three-dimensional instruction. *The Science Teacher, 82*(8), 50.

Kranzfelder, P., Lo, A. T., Melloy, M. P., Walker, L. E., & Warfa, A. R. M. (2019). Instructional practices in reformed undergraduate STEM learning environments: a study of instructor and student behaviors in biology courses. *International Journal of Science Education, 41*(14), 1944–1961.

Lavonen, J., & Laaksonen, S. (2009). Context of teaching and learning school science in Finland: reflections on PISA 2006 results. *Journal of Research in Science Teaching: the Official Journal of the National Association for Research in Science Teaching, 46*(8), 922–944.

Lin, Y. R., Fan, B., & Xie, K. (2020). The influence of a web-based learning environment on low achievers' science argumentation. *Computers & Education, 151*, 103860. https://doi.org/10.1016/j.compedu.2020.103860.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: a meta-analysis. *Child Development*, 1479–1498. https://doi.org/10.2307/1130467.

Lohman, D. F. (1979). Spatial ability: a review and reanalysis of the correlational literature (no. TR-8). Stanford Univ Calif School of Education.

Lopez, E. J., Shavelson, R. J., Nandagopal, K., Szu, E., & Penn, J. (2014). Factors contributing to problem-solving performance in first-semester organic chemistry. *Journal of Chemical Education, 91*(7), 976–981. https://doi.org/10.1021/ed400696c.

Lubinski, D. (2010). Spatial ability and STEM: a sleeping giant for talent identification and development. *Personality and Individual Differences, 49*(4), 344–351.

Lubman, D. I., Cheetham, A., & Yücel, M. (2015). Cannabis and adolescent brain development. *Pharmacology & Therapeutics, 148*, 1–16. https://doi.org/10.1016/j.pharmthera.2014.11.009.

Lucas, B., & Hanson, J. (2016). Thinking like an engineer: using engineering habits of mind and signature pedagogies to redesign engineering education. https://doi.org/10.3991/ijep.v6i2.5366.

Ma, B., Mei, D., Wang, F., Liu, Y., & Zhou, W. (2019). Cognitive enhancers as a treatment for heroin relapse and addiction. *Pharmacological Research, 141*, 378–383. https://doi.org/10.1016/j.phrs.2019.01.025.

Magana, A. J. (2017). Modeling and simulation in engineering education: a learning progression. *Journal of Professional Issues in Engineering Education and Practice, 143*(4), 04017008.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences, 97*(8), 4398–4403.

Marginson, S., Tytler, R., Freeman, B., & Roberts, K. (2013). STEM: country comparisons: international comparisons of science, technology, engineering and mathematics (STEM) education. Final report. Australian Council of Learned Academies, Melbourne, Vic.

Marunic, G., & Glazar, V. (2013). Spatial ability through engineering graphics education. *International Journal of Technology and Design Education, 23*(3), 703–715. https://doi.org/10.1007/s10798-012-9211-y.

Mason, L., Baldi, R., Di Ronco, S., Scrimin, S., Danielson, R. W., & Sinatra, G. M. (2017). Textual and graphical refutations: effects on conceptual change learning. *Contemporary Educational Psychology, 49*, 275–288. https://doi.org/10.1016/j.cedpsych.2017.03.007.

McMahon, D., Cihak, D. F., & Wright, R. (2015). Augmented reality as a navigation tool to employment opportunities for postsecondary education students with intellectual disabilities and autism. *Journal of Research on Technology in Education, 47*(3), 157–172.

McNaughton, B. L., Battaglia, F. P., Jensen, O., Moser, E. I., & Moser, M. B. (2006). Path integration and the neural basis of the 'cognitive map'. *Nature Reviews Neuroscience, 7*(8), 663–678.

Moore, T. J., Glancy, A. W., Tank, K. M., Kersten, J. A., & Smith, K. A. (2014). A framework for quality K-12 engineering education: Research and development. *Journal of Pre-College Engineering Education Research (J-Peer), 4*(1), 2–13. https://doi.org/10.7771/2157-9288.1069.

Mulholland, J., & Ginns, I. (2008). College MOON project Australia: preservice teachers learning about the moon's phases. *Research in Science Education, 38*(3), 385–399. https://doi.org/10.1007/s11165-007-9055-8.

Nardini, M., Jones, P., Bedford, R., & Braddick, O. (2008). Development of cue integration in human navigation. *Current Biology, 18*(9), 689–693. https://doi.org/10.1016/j.cub.2008.04.021.

National Research Council (NRC). (2010). *Standards for K-12 engineering education?* Washington, DC: The National Academies Press.

National Research Council (NRC). (2012). *A framework for K–12 science education: practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

Negen, J., Roome, H. E., Keenaghan, S., & Nardini, M. (2018). Effects of two-dimensional versus three-dimensional landmark geometry and layout on young children's recall of locations from new viewpoints. *Journal of Experimental Child Psychology, 170*, 1–29. https://doi.org/10.1016/j.jecp.2017.12.009.

Newcombe, N. (2017). Harnessing spatial thinking to support stem learning. https://doi.org/10.1787/7d5dcae6-en.

Newcombe, N. S., & Shipley, T. F. (2015). Thinking about spatial thinking: new typology, new assessments. In Studying visual and spatial reasoning for design creativity (pp. 179–192). Springer, Dordrecht.

NGSS Lead States. (2013). Next generation science standards: for states, by states. Retrieved from http://www.nextgenscience.org/. Accessed 8 April 2020.

Novak, J. D. (2002). Meaningful learning: the essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education, 86*(4), 548–571. https://doi.org/10.1002/sce.10032.

O'Keefe, J., & Dostrovsky, J. (1971). The hippocampus as a spatial map: preliminary evidence from unit activity in the freely-moving rat. *Brain Research, 34*, 171–175. https://doi.org/10.1016/0006-8993(71)90358-1.

Olson, D. R. (2004). The triumph of hope over experience in the search for "what works": a response to Slavin. *Educational Researcher, 33*(1), 24–26.

Organization for Economic Cooperation and Development (2017). Education at a glance 2017: OECD indicators. OECD.

Pabuccu, A., & Erduran, S. (2017). Beyond rote learning in organic chemistry: the infusion and impact of argumentation in tertiary education. *International Journal of Science Education, 39*(9), 1154–1172.

Pittalis, M., & Christou, C. (2010). Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics, 75*(2), 191–212. https://doi.org/10.1007/s10649-010-9251-8.

Quirino, P. A. F., Pininga, R. M. C., Barros, M. M., da Costa, P. F. F., de Barros Rodrigues, P. M., de Paula Machado, M. C. F., & Galvão, P. V. M. (2019). Comparison of the prevalence of addiction Internet in Brazilian University students: online cognition scale versus Internet addiction test. https://doi.org/10.36811/ojda.2019.110003.

Roach, V. A., Fraser, G. M., Kryklywy, J. H., Mitchell, D. G., & Wilson, T. D. (2019). Guiding low spatial ability individuals through visual cueing: the dual importance of where and when to look. *Anatomical Sciences Education, 12*(1), 32–42. https://doi.org/10.1002/ase.1783.

Romano, M., Console, F., Pantaloni, M., & Fröbisch, J. (2017). One hundred years of continental drift: the early Italian reaction to Wegener's 'visionary' theory. *Historical Biology, 29*(2), 266–287.

Sampson, V., & Clark, D. (2009). The impact of collaboration on the outcomes of scientific argumentation. *Science Education, 93*(3), 448–484. https://doi.org/10.1002/sce.20306.

Sanchez, C. A., & Wiley, J. (2014). The role of dynamic spatial ability in geoscience text comprehension. *Learning and Instruction, 31*, 33–45. https://doi.org/10.1016/j.learninstruc.2013.12.007.

Schneider, W. J., & McGrew, K. S. (2012). The Cattell-Horn-Carroll model of intelligence. In D. P. Flanagan & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and issues* (pp. 99–144). The Guilford Press.

Shin, N., Choi, S. Y., Stevens, S. Y., & Krajcik, J. S. (2019). The impact of using coherent curriculum on students' understanding of core ideas in chemistry. *International Journal of Science and Mathematics Education, 17*(2), 295–315. https://doi.org/10.1007/s10763-017-9861-z.

Small, M. Y., & Morton, M. E. (1983). Research in college science teaching: spatial visualization training improves performance in organic chemistry. *Journal of College Science Teaching, 13*(1), 41–43.

Sternberg, R. (2000). The concept of intelligence. In R. Sternberg (Ed.), *Handbook of intelligence* (pp. 3–15). Cambridge: Cambridge University Press.

Suh, J., & Cho, J. Y. (2020). Linking spatial ability, spatial strategies, and spatial creativity: a step to clarify the fuzzy relationship between spatial ability and creativity. Thinking Skills and Creativity, 100628. https://doi.org/10.1016/j.tsc.2020.100628.

Tanenbaum, C. (2016). *STEM 2026: a vision for innovation in STEM education*. Washington, DC: US Department of Education.

Taper, M. L., Staples, D. F., & Shepard, B. B. (2008). Model structure adequacy analysis: selecting models on the basis of their ability to answer scientific questions. *Synthese, 163*(3), 357–370. https://doi.org/10.1007/s11229-007-9299-x.

Toivainen, T., Pannini, G., Papageorgiou, K. A., Malanchini, M., Rimfeld, K., Shakeshaft, N., & Kovas, Y. (2018). Prenatal testosterone does not explain sex differences in spatial ability. *Scientific Reports, 8*(1), 1–8. https://doi.org/10.1038/s41598-018-31704-y.

Uttal, D. H., & Cohen, C. A. (2012). Spatial thinking and STEM education: when, why, and how? *In Psychology of learning and motivation* (Vol. 57, pp. 147-181). Academic Press. https://doi.org/10.1016/B978-0-12-394293-7.00004-2.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: a meta-analysis of training studies. *Psychological Bulletin, 139*(2), 352. https://doi.org/10.1037/a0028446.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101*(4), 817.

Wiedenbeck, S., Labelle, D., & Kain, V. N. (2004). Factors affecting course outcomes in introductory programming. In *PPIG* (p. 11).

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465–492. https://doi.org/10.1002/sce.10126.

Xie, C., Schimpf, C., Chao, J., Nourian, S., & Massicotte, J. (2018). Learning and teaching engineering design through modeling and simulation on a CAD platform. *Computer Applications in Engineering Education, 26*(4), 824–840. https://doi.org/10.1002/cae.21920.

Zollman, A. (2012). Learning for STEM literacy: STEM literacy for learning. *School Science and Mathematics, 112*(1), 12–19.

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