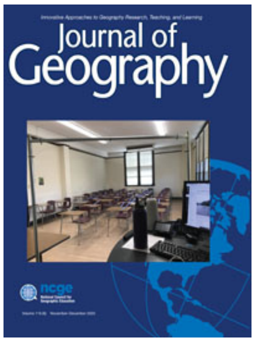

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Using Eye Tracking to Explore Differences between High and Low Map-Based Spatial Ability

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ABSTRACT

In this article, we use eye-tracking technology to analyze the eye movement differences in cognitive maps between high and low level map-based spatial ability participants, revealing key factors of superior spatial ability. It is found that focusing on the perception of spatial structure information, constructing and manipulating complex images psychologically, and positioning by spatial relationship with reference objects are three key factors of superior spatial ability. Based on this, we developed the teaching strategies of geospatial ability to provide reference and suggestions for the education and evaluation of senior high school students' spatial ability.

KEYWORDS

Eye tracking; spatial ability; map cognition; senior high school student; teaching strategies

Introduction

Human beings live in a spatial environment. We have the ability to determine the spatial positioning of geographical entities and explore the spatial structure between these entities, which is the basis of solving space problems. Spatial ability is defined as the ability to perceive, learn, remember, reason and transmit spatial information. It originated from the concept of the cognitive map put forward by American cognitive psychologist Tolman (1948). A cognitive map is a kind of psychological representation, which refers to acquiring, coding, storing, recalling and decoding information about the relative location and attributes of phenomena in space environment (Kitchin 1994). Spatial ability is the underlying ability to construct a map. It affects the acquisition of the map's information, especially the extraction of spatial structure information, such as relative position and the change between geographical things (Self and Golledge 1994). In our daily life, we use spatial ability to identify locations on maps. Studies indicate that stronger spatial abilities have a positive effect on people's understanding of items in different fields, such as music, graphic design, medicine, and sense of direction (Douglas and Bilkey 2007). Therefore, spatial ability draws wide attention among researchers and educators.

The evaluation and cultivation of spatial abilities is a key field in geography research. However, spatial ability is hard to explain and cultivate. The lack of reliable and up-to-date spatial ability assessment tools leads to the difficulty of implementation of spatial ability measurements (Jeng and Chen 2007). Although students' thinking methods or thought processes can be understood through interviews, the results often do not reflect their subconscious cognitive process because of sampling limitations (Chen, Lai, and Chiu 2010). Maps are the true reflection of surface space, and cognitive maps play an important role in reflecting an evaluators' interpretation of a subjects' spatial ability. Furthermore, the cognitive patterns of maps are also conducive to the cultivation of spatial abilities. As a sensory system to receive information from the outside world, eye movement can reflect the brain's thinking process and reveal the internal mechanism of cognitive processing (Wang, Chen, and Lin 2014). Tracking eye-movement provides clear, real-time evidence of subjects' internal reflections and motivations that are impossible to disguise (Salvucci and Anderson 1998; Shimojo et al. 2003).

Therefore, in this study, we constructed a spatial ability evaluation model based on eye movement indicators, and divided the subjects into high and low spatial abilities group based on scores generated by the model. Then, by comparing the eye trajectories of cognitive maps between high and low ability groups, we analyzed the key factors of superior spatial ability, and put forward teaching strategies for developing spatial abilities.

Literature review

Spatial ability

Spatial ability is the basis of cognitive mapping; it is important in the process of perception, encoding, conversion, and extraction of map information. As a result, the components of spatial abilities are also quite complex. Linn and Petersen (1985) divided spatial abilities into three categories: spatial perception, mental rotation and spatial visualization. Dong et al. (2018) believes that the differences in map-based spatial ability between geographers and non-geographers is mainly reflected in spatial localization, spatial orientation

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and spatial visualization. Garlandini and Fabrikant (2009) suggest that how to use maps to present spatial localization information and the development of spatial orientation should be the focus of geography. Since the purpose of this study is to reveal the patterns of map cognition, the components of spatial abilities must be able to reflect the entire process of map cognition. Spatial cognition includes the process of selecting, processing, encoding, storing and extracting spatial information. In the process of map cognition, the subjects need to integrate and process map information first, so the ability to perceive map information is fundamental. Then, in the information processing and coding step, subjects perform complex operations and transformations on spatial images mentally. Finally, the storage and extraction of information is the positioning of map information, as well as the presentation of spatial cognitive results. Based on the concepts above, we define spatial ability as spatial perception, mental rotation and spatial positioning ability. These abilities form the basis of spatial thinking in our daily lives and are applied in various fields. Spatial perception is defined as the ability to visualize how to view the structure of the same area from different perspectives; mental rotation is defined as the ability to make two-dimensional or three-dimensional changes such as the rotation, twisting, and turning of space objects through imagination; and spatial positioning is defined as the ability to orient oneself by local, relational, or global frames of reference (Self and Golledge 1994).

Because each link of map cognition requires spatial ability, and each component of spatial abilities can also correspond to different links of map cognition, the results of map cognition can potentially objectively reflect the level of individual spatial ability. The theory of spatial cognition can also explain different spatial abilities (Hegarty and Waller 2004). Many researchers have explored the use of cognitive maps to evaluate and cultivate spatial ability. Ooms et al. (2015) used a questionnaire to evaluate the spatial ability of middle school students, which included 20 questions based on five topological maps. Testing includes sub-tasks such as spatial visualization, measurement and navigation. Kovach, Surrette, and Aamodt (1988) asked the subjects to reach a specific destination according to the goal in the street map, and used driving time as an indicator to evaluate the spatial ability of the subjects. The Navigation Map Reading Ability Test (NMRAT) developed by Lobben (2007) consists of five parts: map rotation, location recognition, self-localization, route memory and path-finding exercises. Spatial localization is an important part of NMRAT, but only the response time of the subjects is considered in the score. All the researches mentioned above are based on the number of correctly answered questions or the response time to evaluate spatial ability. But it has not been evaluated from a cognitive perspective.

In addition, there are many studies on spatial abilities of gender differences, and the conclusions are mixed. For example, some studies believe that there is no gender difference in spatial abilities (Beaumont et al. 1984; Montello et al. 1999). Yet there are some studies that claim the opposite (Montello and Pick 1993; Malinowski and Gillespie 2001).

Eye-tracking methods to explore map-based spatial cognition

Eye tracking technology provides technical support for exploring map cognitive processes. An eye tracker records the user's eye movement data at a specific rate (e.g., 100 Hz) and enables the researcher to analyze the user's visual and attention processes (Duchowski2007). Because the brain dominates the movement of sight, the process of eye movement reflects the processing of visual information in the brain, and can reveal the inner mechanism of cognitive processing (Goldberg et al. 2002). Fixations and saccades are the main measurements used in eye-tracking analysis, which are two basic components of eye movement. Fixations refer to the position where eyes stay on the screen for a certain time, and saccades refer to the rapid movement between fixations. The subject's perception of the scene is accomplished by alternating between fixations and saccades (Liao et al. 2016).

In recent years, there have been many studies on map cognition using eye tracking technology. Wang, Chen, and Lin (2014) and others summarized the training strategies of geospatial ability on the basis of tracking and compared the eye movement characteristics of subjects with high and low spatial ability groups when completing spatial recognition, graphic conversion, spatial rotation and reasoning problems. Kim et al. (2015) tracked the eye movement process of subjects in different experimental situations to complete spatial observation and positioning tasks and explored the influence of different experimental situation design on eye movement characteristics of subjects. They encouraged teachers to guide students to achieve the desired learning effect by designing targeted task situations. Kuchinke (1996) and others validated the influence of map elements on spatial positioning results by analyzing the effects of map elements such as square grid and topographic map background on eye movement indicators (e.g., fixation time, fixation counts). Dong et al. (2018) evaluated students' map skills based on eye tracking technology from three aspects: first fixation, process fixation and search fixation. The measurement relationship between map reading and eye movement was established, which provided an example for constructing a map-based evaluation model using eye movement indicators. These studies show that eye tracking can reflect the pattern of map cognition. Therefore, this study attempts to use eye movement indicators related to the first fixation, processing and search to evaluate spatial ability. And by analyzing the eye movement trajectories between different level map-based spatial ability subjects, they reveal key factors of superior spatial ability.

Empirical study

Methodology

We used an eye tracker to track and record the spatial visualization of 62 high school students. Eye tracking technology was used to record the subjects' eye movement process in completing spatial tasks and also provides eye movement indicators for evaluating geospatial ability. We referred to a spatial ability evaluation model based on eye movement indicators which were the first fixation, processing and search. We used structural equation modeling to verify the relationship between eye movement indicators and spatial ability. Using the subjects' spatial ability scores generated by the model, we classified the subjects into a high spatial ability group and a low spatial ability group. We also used correctness of task completion to verify the validity of the model score. Then we compared the eye movement trajectories of high and low spatial ability groups in the process of completing spatial tasks. At the same time, we also conducted interviews with the subjects, and the results of the interviews served as our basis for judging their cognitive processes. Eye tracking results obtained in the study and interview records were integrated and analyzed using quantitative and qualitative research methods to present the final research conclusions and eye movement data. Next, we revealed the key factors of the superiority in spatial ability from three aspects: spatial perception, mental rotation and spatial positioning. Finally, we put forward the teaching strategies for the cultivation of high school students' geospatial ability.

Subjects

The subjects were 62 senior high school students (23 boys and 39 girls, with an average age of 16.5 years) randomly selected from Shanghai JianPing Middle School and Suzhou No. 3 Middle School. They were selected as early screening subjects for eye movement experiments. All subjects had normal uncorrected or corrected visual acuity. The subjects whose eye movement data missing rate was more than 30% due to the excessive number of blinks, were excluded. 55 valid subjects remained in the study group.

Experimental design

The eye movement experiment in this study consisted of three map-based spatial positioning tasks, which were developed in consultation with senior high school geospatial ability research experts. After the preliminary experiment and discussion of 8 postgraduates majoring in geography education in the research group, we revised the experimental task. Finally, the test questions were converted into visual stimulus materials for this study. All materials were presented in Chinese, which was the native language of the subjects.

In the experiment, the subjects were shown a realistic local campus map from Google Maps and asked to observe and memorize the spatial location and name of buildings and road signs within a limited time (15 seconds). There were five buildings (expressed by 1/2/3/4/5) and two streets (expressed by 6/7) on the map. After the map was displayed for 15 seconds, the screen switched to the map task page. The specific tasks are as follows:

- Task #1: The subjects were asked to locate building 5 on a blank map presented in the next 10 seconds and keep their eyes fixed at the center of the building after the building was located. After the task requirement was rendered, a blank map was displayed and the subjects carried out the required task. When the subjects believed that they located the building, they kept their eyes fixed until the picture automatically switched.
- Task #2: Before the task requirement was displayed, the same local map used in Task #1 was presented to the subjects again for 10 second to eliminate the influence of the subjects' different memory capacity. Then the subjects were asked to locate building 4 on a blank map rotated 30 degrees clockwise within 10 s. Like in Task #1, the subjects carried out the task in the next 10 seconds and kept their eyes fixed at the building until the display of map ended.
- Task #3: Once again, the original partial map was presented for 5 seconds and the subjects were asked to locate building 3 on a map within 15 seconds. The map was the same map presented to the subjects and being rotated for a certain angle. The subjects were not informed of the rotation angle of the new map, but there were three references in the map, such as building 5, road 6 and road 7.

All the spatial tasks involved map-based spatial perception, mental rotation and map-based spatial positioning ability. The tasks were sequenced by their complexity, from the lowest to the highest, which was consistent with the students' cognitive process. At the same time, considering the distribution of key information in map materials, we completed statistical analysis of the largest rectangular area covered by the original map and all the image identifiers in the new map as the area of interest (AOI).

Experiment implementation

Eye Control V2.0 Eye Moving instrument, developed by Shanghai Qingyan Technology company, was used as the eye tracker in this study. The sampling frequency of this instrument is 100HZ, and the instrument size is 33 cm $\times$ 10 cm $\times$ 4.5 cm. It can be directly installed under the computer monitor, and is easy to move and carry. The monitor is used to present the experimental material and record the eye movement data completed by the subjects.

To protect the interests of the subjects and the scientific nature of the experiment, our experiment was designed and implemented in accordance with the requirements of the Human Subject Protection Committee of East China Normal University. Before the subjects entered the laboratory, they were instructed on the purpose, process, and precautions of the experiment. They were also trained with spare map materials in paper form to get familiarized with the experimental process in advance.

The experimental site was free from any interference. The subjects were seated in an adjustable seat in front of the material display screen without wearing any equipment. They were allowed to move in a small range to adjust to the optimal position. One at a time, the subjects took turns performing eye movement experiments. Before the beginning of the experiment, the eye tracker was calibrated for each subject to ensure the continuity and accuracy of eye tracker data. The experiment also excluded data with a missing rate greater than 30%.

Interview

In order to reveal the spatial cognitive process of the subjects more comprehensively, each subject was interviewed alone after the eye movement experiment. The interview focused on the information perception of the presentation map materials as well as eye movement changes and strategy applied in the task completion process. The interview included the following questions:

- For task #1: How did you observe the local campus map and what strategies did you take? How did you locate building 5, and what methods did you take?
- For task #2:Has the method of observing local campus maps changed from task#1? How did you locate building 4, and what methods did you take?
- For task #3: Has the method of observing local campus maps changed from task#1 and task#2? How did you locate building 3, and what methods did you take?

The interviews helped researchers analyze changes in eye movement trajectories of the subjects in order to better understand the difference in eye movements between high and low spatial ability subjects.

High and low spatial ability group division

Based on previous research results (Kuchinke 2015; Dong 2018), we constructed a geospatial ability evaluation model based on eye movement indicators (as shown in Figure 1). There are two eye movement indicators for each of the three aspects of the first fixation, processing fixation and search fixation. The first fixation (X1) includes the time to first fixation (a1) and the first fixation duration (a2). Both indicators are about the area of interest (AOI). The former one refers to the first time the subjects enter the region of interest from the beginning of fixation to the first time. The latter one indicates the time spent between the first entry and the first exit from the AOI. Because the key information of the map is distributed within the area of interest, the study found that the quicker the subjects entered the region of interest, the more accurate the subjects positioned the information (Ooms, Maeyer, and Fack 2014). The longer the first fixation time, the more information processed in the first reading of the AOI. The two indicators reflect the perceived efficiency and accuracy of key information more pertinently (Goldberg and Kotval 1999). The time to first fixation is inversely proportional to spatial ability and the first fixation duration is directly proportional to spatial ability. Processing fixation (X2) was measured by the fixation count percentage (b1) and the fixation duration percentage (b2) (Ooms, Maeyer, and Fack 2014). They refer to the percentage of AOI's fixation time during the completion of the task, and the percentage of AOI's fixation counts to the total number, which are used to measure the interest and attention of the subject. They are all proportional to the spatial ability. The search fixation (X3), including saccade count (c1) and saccade length (c2), are the search statistics of the whole map material in the experimental process. The more scans the subjects spent on the target search, the more energy they spent on the target search. It also reflects that there may be some obstacles to the acquisition of information (Goldberg and Kotval 1999). They are all negatively correlated with the spatial ability.

We recorded the eye movement indicators of the subjects as they completed each task. Then we used the structural equation model to explore the effects of various eye movement indicators on geospatial ability. The results show the parameters for all three first-level indicators (X1, X2, X3) are significant at $P = 0.05$ level (Table 1). The path coefficient of the search indicator has the largest difference between the three tasks, and the overall effect is smaller than the first fixation indicator and the process indicator. Even the path coefficient of the search indicator in task #3 is negative. Both the first fixation indicator and the processing indicator indicate the ability to capture key information, while the search indicator indicates the search efficiency in the process of completing the spatial task. Therefore, focusing on the key information quickly and intensively is helpful for better positioning performance. The subjects with better geospatial ability can screen the key information more accurately and quickly, and concentrate mostly on the key information area (AOI). Relatively speaking, the search efficiency of subjects to the target is less important, because they must constantly scan, search key information, and determine spatial association, especially in complex spatial tasks. The shorter the time spent, the more likely the subjects are to miss key information. This is consistent with the findings of Ooms, Maeyer, and Fack (2014). The results of the path coefficient of the secondary indicator also support this conclusion.

After determining the relationship between each indicator and geospatial ability, we used min-max normalization to convert each eye movement data and scored each subject's geospatial ability based on the evaluation model. To evaluate the scores generated by the model, we tested them against the results of each subject's task completion. For each task, the subjects were divided into two groups based on whether or not they completed each task accurately. After homogeneity test of variance, the independent sample T test was used to explore the significance of the differences in the geospatial ability scores between the correct and incorrect subjects. The results show (as shown in Table 2) that the correct group and the incorrect group have significant differences in geospatial ability scores. In all three tasks, subjects who completed the task correctly scored significantly higher in terms of geospatial ability than other subjects. This showed that the accuracy of subjects has been reflected in the scores generated by the model and further verified the credibility of the evaluation model.

Finally, we took the first 27% (15) and the last 27% (15) of the geospatial ability scores as the high spatial ability group and the low spatial ability group, respectively, to explore the pattern of their eye movement changes.

Results and discussion

The eye movement characteristics of the subjects with high and low spatial ability were explored from three aspects: spatial perception, mental rotation and spatial positioning. By

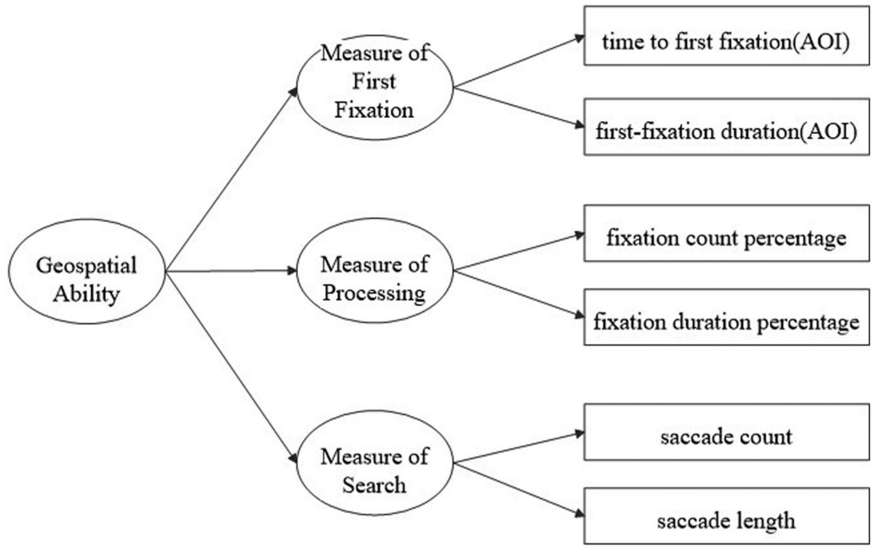


Figure 1. Geospatial ability evaluation model.

Table 1. Eye movement index path coefficient (n = 55).

Path Coefficient	Task #1	Task #2	Task #3
Y→X1	0.939*	0.960*	0.987*
X1→a1	0.805*	0.800*	0.801*
X1→a2	0.965*	0.961*	0.985*
Y→X2	0.919*	0.949*	0.982*
X2→b1	0.992*	0.993*	0.980*
X2→b2	0.938*	0.942*	0.904*
Y→X3	0.676*	0.717*	−0.768*
X3→c1	0.882*	0.835*	0.337*
X3→c2	−0.412*	−0.284*	−0.867*

Table 2. Difference test between correct and incorrect participants' geospatial ability scores (n = 55).

Test	Group	Number	Mean	T	P
Task #1	Correct	43	72.666	4.310	0.023*
	Incorrect	12	50.558		
Task #2	Correct	36	76.747	3.130	0.002*
	Incorrect	19	53.047		
Task #3	Correct	31	74.417	9.225	0.000*
	Incorrect	24	52.578		

replaying all of the high and low spatial ability subject's eye movement trajectories through the recording function of the eye tracker and analysis of the interviews, we found significant differences between high- and low-level subjects' patterns. The typical subjects in task #3 were taken as examples to illustrate.

Map-based spatial perception ability

As shown in Table 3, we selected three subjects from each group as examples to show the differences of spatial information perception between high and low spatial ability subjects. The high spatial ability subjects are NO.1, NO.16, NO.32 and the low spatial ability subjects are NO.4, NO.6, NO.12. Their biggest difference is varying emphasis on spatial information perception and acquisition. As Kulhavy and Stock (1996) pointed out, maps contain two different kinds of information: feature information and structure information. Feature information includes the features of each object in the graph, such as logo, name, and other visual factors, such as color, shape and size. Structural information emphasizes spatial relationships among map elements, including "geometric and metric relationships among different objects, and boundaries and routes of various elements in map space" (Kulhavy and Stock, 1996). By replaying the subjects' eye tracking during the tasks, we found that almost all the high spatial ability subjects' eye tracking lock key information areas faster than subjects in the other group and glance between buildings and roads. They pay more attention to the spatial relationship between map objects and grasp the overall structure of the map through the relative positions of different objects. From the analysis of eye movement indicators above, we also find subjects with high spatial ability can quickly and accurately perceive the key information in map materials, such as the area of interest (AOI). Therefore, both the eye movement indicator and the eye movement trajectories indicate that subjects with high spatial perception ability can find key information areas more accurately and pay more attention to the spatial structure information of the map. Moreover, high ability subjects can selectively extract key information on the basis of subjective judgment, such as NO.16's comment in the interview that in order to reduce the burden of memory, only a part of the diagonal key area was focused on.

In contrast, low spatial ability subjects only focused on feature information extraction. The interview of No.4, No.6 and No.12 subjects mentioned that they paid more attention to the names of the map objects and forcibly memorized the spatial positioning of the building with a fixed mindset and ignored the spatial relations between them. They only focused on mechanical memorization of feature information, but did not pay attention to structural information. After the map is rotated, therefore, they cannot find the correct position of the target.

Map-based mental rotation ability

Kim et al. (2015) confirmed that the perception and processing strategy of map information would be transferred to the

Table 3. Characteristics of typical high and low ability subjects in the original map.

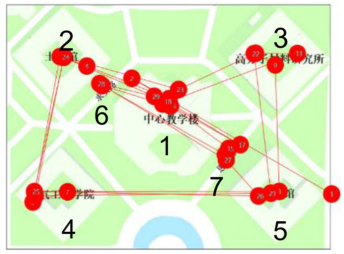
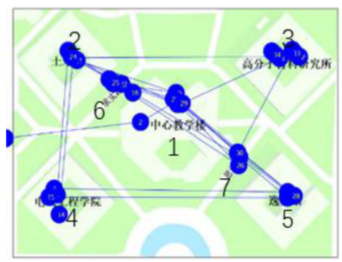
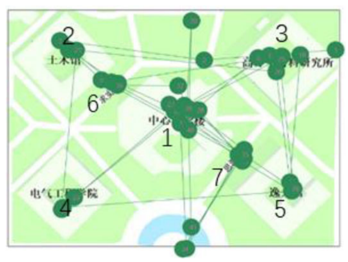
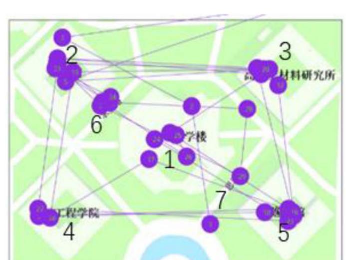
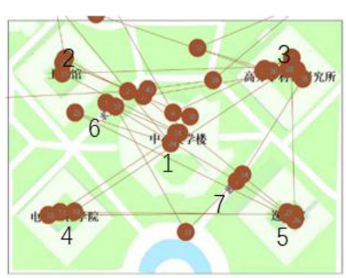
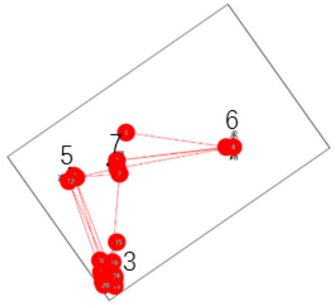
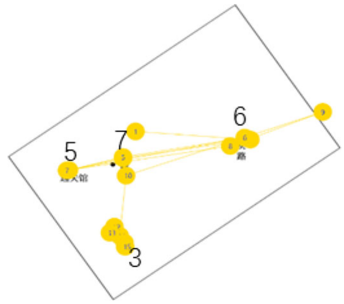
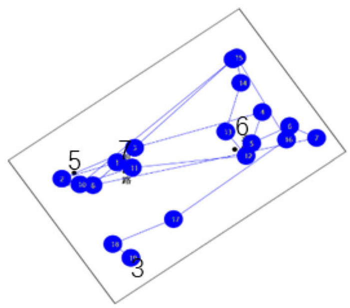
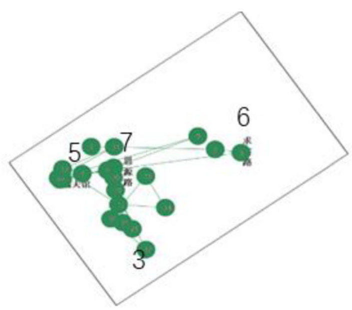
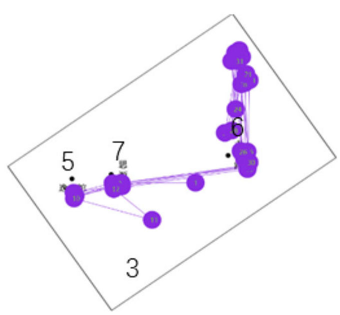
Group	Number	Eye Track	Interview Record
High spatial ability	1		"Look at the corner of the four buildings, then look at the two roads. The road 6 is close to building 2, the following is building 4, the road 7 is close to building 5, and the above is building 3."
	16		"There are two roads, just look at this diagonal line, and then look at building 3 in the upper right corner."
	32		"Remember the relative positions of the four buildings, and then find the road 1 near building 2, road 2 near building 5, they are all on a diagonal line."
Low spatial ability	4		"Memory according to the order of the first latter, then road 1 is above, and road 2 is below."
	6		"I see the order from building 1 to the surrounding areas. The order of building 2 - building 4 - building 5 - building 3 is always forgotten when I look at it."
	12		"I don't have any idea, just watch one by one."

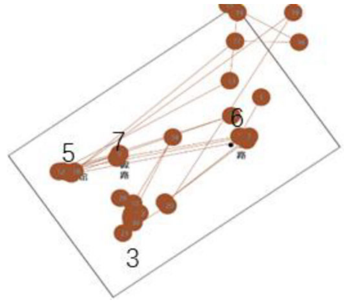
Table 4. Characteristics of typical high and low ability subjects in the new map.

Group	Number	Eye Track	Interview Record
High spatial ability	1		"Building 3 was originally located above building 5 and near road 2, so it should be in the lower left corner after rotation."
	16		"This diagonal line should be located in the building 2, it is in the upper left corner in the original map, and building 3 is in the upper right corner, so it can be judged in this position."
	32		"First of all, we can see the location of building 5. The road 2 and the road 1 are in a diagonal line. According to this, we can judge that the picture rotates about 180 degrees. Then we can judge the location of building 3."
Low spatial ability	4		"I still judge what building that position should be in the order of the first latter, which is very slow."
	6		"I'm wrong. I'm confusing building 3 with the Institute of Electrical Engineering."

(*continued*)

subsequent map tasks through the research. Therefore, as shown in Table 4, the six typical subjects above are also used as examples to present the difference of high and low spatial ability subjects in mental rotation and spatial positioning in the process of task #3. According to the analysis of eye tracking and interviews, we found that subjects with high spatial ability can perform a series of complex operations such as rotation, comparison, and matching on

Table 4. Continued.

Group	Number	Eye Track	Interview Record
	12		"I was confused when I saw this picture. I didn't know how to do it, and then I guessed the location at random."

map objects in mind based on the perception of the spatial structure of the map, thereby achieving the positioning of spatial information. For example, subject NO.32, after mastering the spatial structure of the map, determined the rotation direction and angle of the original map by the given reference. Subjects NO.1 and NO.16 mentally compared the spatial orientation of the reference object with the spatial positioning of the target object, and finally located the target object.

Map-based spatial positioning ability

Based on the interview records and eye movement characteristics, we found that the high spatial ability subjects commonly adopted two strategies for target positioning. First, they compared the target with other buildings and used other objects given in the task#3 map to identify the position of the target. The relative position and distance between the two are located, such as completed by subjects No.1 and No.16; second is to determine the rotation direction and angle of the original map by the given map object, so that the task #3 map corresponds to the original map mode, and then complete positioning, such as completed by subject No.32. Obviously, their spatial positioning ability is strong, and the latter's mental rotation ability is also very strong. Comparatively, the low spatial positioning ability adopts certain strategies based on the obtained characteristic information, such as sequential positioning, only based on the perception of characteristic information, with weak mental rotation and spatial positioning.

According to the analysis of eye movement characteristics of high and low spatial ability subjects, great differences in spatial cognitive processes of different abilities are found and the key factors of superiority of spatial ability are summarized. Firstly, in the aspect of spatial perception, we should pay attention to the acquisition of map structure information, understand the spatial relationship between map objects, grasp the overall spatial structure of the map, put structure information as the main part and feature information as the supplement. And, with high spatial ability, students can transfer the perceived spatial structure information to the subsequent spatial cognitive process, such as mental rotation and spatial positioning, and adopt corresponding positioning strategies. For example, the location of the target can be judged by referring to other objects given in the map, that is, by comparing the relative position and distance between the target and other buildings, or judging the rotation direction and angle of the original map by the given map objects, so that the new map corresponds to the original map pattern. This reflects two key factors of superior geospatial ability in terms of mental rotation and spatial positioning: the ability to locate the target according to the location and distance of other objects and the ability to psychologically rotate and compare a series of complex images. These key factors are the basis of cultivating geospatial ability.

Spatial ability instructional strategy

Based on the results, this study puts forward training strategies to improve high school students' geospatial ability. Using maps as an important teaching tool, high school students' geospatial ability can be improved through training in three aspects of spatial perception, mental rotation and spatial positioning in daily geography teaching. Strategic perception of a map's spatial information is the basis of cultivating geospatial abilities. Teachers can integrate the cultivation of geographical spatial abilities into geography teaching. In daily map reading training, students are trained to extract and grasp the structural information of the map and key characteristic information. The observation of the original map material in the experiment is taken as an example (as shown in Figure 2). First, students are guided to combine each object with the orientation. For example, in the center is building 1, and the upper left corner is building 2. In the upper right corner is building 3. Then the spatial relationship of each object is introduced. Building 2 and 3 are in a row, building 2 and 4 are in a column, building 2 and 5 are on a diagonal line. Road 6 is between building 1 and 2, and road 7 is between building 1 and 5. On the basis of mastering the overall spatial structure of the map, students are further trained on mental rotation ability by learning how to construct mental maps, which helps students to rotate and compare complex images psychologically. Related map tasks should be provided, such as locating the position of a target object in a blank rotated map or finding images that meet teacher's requirements among different images. At the same time, students are guided to use positioning

Figure 2. A sample map material.

strategies, such as finding a reference object, and quickly locating the target location based on the location of the reference object. Formulating a similar program to train students in stages and using eye tracking technology to compare the effect of spatial ability before and after training can be a future research direction.

Discussion

In this study, we used eye tracking technology to observe the geospatial ability of high school students. In the first phase, the study used eye movement indicators and accuracy indicators to classify all subjects into high and low spatial ability groups. The eye movement trajectories and interview records of high and low ability subjects were then compared to determine key factors that led to proficiency in choosing the correct answer. These three key factors are spatial perception, mental rotation, and spatial positioning. Map cognition is the process of sensing, encoding, and extracting map information, so these three factors are indispensable. Through research, we found that high spatial ability subjects perform spatial information perception, mental rotation and spatial positioning strategies, and then extend it to students' spatial ability training.

Through comparison of eye movement indicators and observation of eye movement trajectories, we find that subjects with high spatial ability are able to capture critical information quickly and accurately. This is also one of the significant advantages of high spatial ability subjects. They pay more attention to the acquisition of spatial structure information and pay attention to the spatial relationship between objects in the map. The low spatial ability subjects only pay attention to the feature information of the map, and are limited to the names and signs of each object in the map. Obviously, the subjects who pay attention to the structural information can locate the interest area of the map more quickly and accurately in the subsequent positioning tasks, and capture the key information in the map (Tsai et al. 2012), which lays the foundation for mental rotation and spatial positioning. Subjects with high spatial ability can construct maps in mind by using the spatial structure information of perception and perform a series of complex operations on the mental map, so as to correspond the new map pattern constructed with the original map pattern. In general, their spatial reasoning ability, one type of spatial abilities, is better. Further, by finding a reference object, the relative position and distance with the reference object are compared to complete the spatial positioning.

Researchers have found that spatial abilities can be improved through appropriate teaching and training (Alias, Gray, and Black 2002; Idris 2005; Martín-Gutiérrez et al. 2010). Based on the superiority of high geospatial ability in spatial perception, mental rotation and spatial positioning, we proposed strategies for the improvement of high school students' spatial ability using experimental maps as an example. The map is a valid expression of the real three-dimensional surface space and is the spatial basis for geography teaching. The study can use maps to improve students' spatial perception ability, mental rotation ability and spatial positioning ability. The three-dimensional maps can help students build spatial imagination, and then process the images in mind. Wang, Chen, and Lin (2014) found that spatial perception, spatial vision, and mental rotation are the main factors of students' superior geospatial ability in the research using eye trackers to improve the student's geospatial ability. They carried out spatial training for three months using maps. Through post-testing, it was found that the spatial vision and spatial perception of all students significantly improved, with only some students improving in mental rotation.

Starting from the three factors that affect geospatial abilities in this study, the corresponding geospatial ability training can be formulated. In daily map reading training, students should be trained to master the overall structure of the map and extract key information, especially, the spatial relationship of each object in the map. At the same time, teachers should pay attention to the students' ability to construct and manipulate maps. The training of mental rotation ability can help students construct and manipulate complex images with the help of solid model training. For example, let students complete the positioning task by manipulating the solid model. In this process, students can deepen spatial cognition and gradually build up spatial thinking ability. Further, when the target positioning is performed, the position of the target object is determined by comparing the relative position and distance between the positioning target and other buildings. This requires students to pay attention to the overall structure when they perceive the map. If they rely solely on feature information, such as name, shape, etc., they will increase the memory burden and the overall grasp of the map is not solid. But based on structural information, the spatial relationship between objects can be better grasped, and the target can be located quickly and accurately.

The higher proportion of female students in the study may impact the results. Studies have shown that the gender difference in spatial ability depends on the level of memory load. Brown, Lahar, and Mosley (1998) found that gender differences disappeared when the memory load was low, such as completing spatial tasks under the condition of presenting a map. Ward, Newcombe, and Overton (1986) did not find gender differences in map present condition (low memory load). Males performed better than females when the map was absent (high memory load). In the experiment process of this research, the original map material was repeated as much as possible to eliminate the memory load of the subjects. Therefore, we believe that the influence of gender factors on the measurement results of spatial ability in this study may not be obvious. Different types of spatial tasks (high and low memory load) need to be designed to explore gender differences in spatial ability. This provides a new research direction in the future.

Conclusion

Combining eye tracking technology with research on map-based spatial abilities, we identified three key factors measuring students' map-based spatial ability development level and proposed teaching strategies to facilitate growth in students' spatial abilities. By analyzing the eye movement experiment process of high and low spatial ability subjects based on maps, we have found that the main factors of spatial superiority are spatial perception, mental rotation and spatial positioning. Starting from the above three factors, teachers can use map tools to focus on cultivating students' spatial perception ability, mental rotation ability and spatial positioning ability to improve their spatial ability level.

There are also some shortcomings in the study. Due to the limitations of the eye movement experimental equipment, the number of samples participating in the eye movement experiment is small. Strict screening of subjects, longer experimental time, and higher environmental requirements all pose greater difficulties for sample selection in eye movement experiments. In the future, we will further expand the number and type of samples to explore the universality of the research results. In addition, the analysis and processing of eye movement data is not sufficient and thorough. Later, more impact factors should be included to analyze the differences in eye movement characteristics of high and low spatial subjects, such as the memory ability of the subjects.

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Notes on contributors

Yuyu Sun is responsible for experiment implementation and thesis writing.

Xiaoxu Lu is responsible for research design and overall control.

Yan Wang is responsible for the revision of the article and the supplement of key information.

References

Alias, M., D. E. Gray, and T. R. Black. 2002. Attitudes towards sketching and drawing and the relationship with spatial visualization ability in engineering students. *International Education Journal* 3 (3): 165–75.

Beaumont, P., J. Gray, G. Moore, and B. Robinson. 1984. Orientation and wayfinding in the Tauranga Departmental Building: A focused post-occupancy evaluation. *Environmental Design Research Association Proceedings* 15:77–91.

Brown, L. N., C. J. Lahar, and J. L. Mosley. 1998. Age and gender related differences in strategy use for route information. A map present direction giving paradigm. *Environment and Behavior* 30 (2): 123–43. doi: 10.1177/0013916598302001.

Chen, H.-C., H.-D. Lai, and F.-C. Chiu. 2010. Eye tracking technology for learning and Education. *Journal of Research in Education Sciences* 55 (4):39–68. http://www.ntnu.edu.tw/acad/jres/eng/j55/j554.

Dong, W., Y. Jiang, L. Zheng, B. Liu, and L. Meng. 2018. Assessing map-reading skills using eye tracking and Bayesian structural equation modelling. *Sustainability* 10 (9):3050. doi: 10.3390/su10093050.

Douglas, K. M., and D. K. Bilkey. 2007. Amusia is associated with deficits in spatial processing. *Nature Neuroscience* 10 (7):915–21. doi: 10.1038/nn1925.

Duchowski, A. 2007. *Eye tracking methodology: Theory and practice*. 2nd ed. London: Springer.

Garlandini, S., and S. I. Fabrikant. 2009. Evaluating the effectiveness and efficiency of visual variables for geographic information visualization spatial information theory. In *Proceedings of the International Conference on Spatial Information Theory*, Brittany France, 21–25 September 2009; Berlin, Germany: Springer; pp. 195–211.

Goldberg, J. H., and X. P. Kotval. 1999. Computer interface evaluation using eye movements: Methods and constructs. *International Journal of Industrial Ergonomics* 24 (6):631–45. doi: 10.1016/S0169-8141(98)00068-7.

Goldberg, J. H., M. J. Stimson, M. Lewenstein, N. Scott, and A. M. Wichansky. 2002. Eye tracking in web search tasks: Design implications. In *Proceedings of the 2002 Symposium on Eye Tracking Research & Applications*, New Orleans, LA, 25–27 March; pp. 51–58.

Hegarty, M., and D. Waller. 2004. A dissociation between mental rotation and perspective-taking spatial abilities. *Intelligence* 32 (2): 175–91. doi: 10.1016/j.intell.2003.12.001.

Idris, N. 2005. Spatial visualization and geometry achievement of form two students. *Jurnal Pendidikan*, 29–40. http://myais.fsktm.um.edu.my/5419.

Ishikawa, T. 2016. Spatial thinking in geographic information science: students' geospatial conceptions, map-based reasoning, and spatial visualization ability. *Annals of the American Association of Geographers* 106:76–95.

Jeng, H.-L., and S.-Y. Chen. 2007. Model exploration and validation of the standardized spatial ability test. *Journal of Educational Research and Development* 3 (4):181–216. http://journal.naer.edu.tw/uploadfiles/0vol011_07vol011_07.pdf.

Kim, K., M. Kim, J. Shin, and J. Ryu. 2015. Eye-movement analysis of students' active examination strategy and its transfer in visuospatial representations. *Journal of Geography* 114 (4):133–45. doi: 10.1080/00221341.2014.991420.

Kitchin, R. M. 1994. Cognitive maps: What are they and why study them. Journal *of Environmental Psychology* 14 (1):1–19. doi: 10.1016/S0272-4944(05)80194-X.

Kovach, R. C., M. A. Surrette, and M. G. Aamodt. 1988. Following informal street maps: Effects of map design. *Environment and Behavior* 20 (6):683–99. doi: 10.1177/0013916588206002.

Kuchinke, L., F. Dickmann, D. Edler, M. Bordewieck, and A. Bestgen. 2016. The processing and integration of map elements during a recognition memory task is mirrored in eye-movement patterns. *Journal of Environmental Psychology* 47:213–222. doi: 10.1016/j.jenvp.2016.07.002.

Kulhavy, R. W., and W. A. Stock. 1996. How cognitive maps are learned and remembered. *Annals of the Association of American Geographers* 86 (1):123–45. doi: 10.1111/j.1467-8306.1996.tb01748.x.

Liao, H., W. Dong, C. Peng, and H. Liu. 2016. Exploring differences of visual attention in pedestrian navigation when using 2D maps and 3D geo-browsers. *Cartography and Geographic Information Science* 44 (6):474–90. doi: 10.1080/15230406.2016.1174886.

Linn, M. C., and A. C. Petersen. 1985. Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development* 56 (6):1479–98. doi: 10.2307/1130467.

Lobben, A. K. 2007. Navigational map reading: Predicting performance and identifying relative influence of map-related abilities. *Annals of the Association of American Geographers* 97 (1):64–85.]. doi: 10.1111/j.1467-8306.2007.00524.x.

Malinowski, J. C., and W. T. Gillespie. 2001. Individual differences in performance on a large-scale, real-world wayfinding task. *Journal of Environmental Psychology* 21 (1):73–82. doi: 10.1006/jevp.2000.0183.

Martín-Gutiérrez, J., J. Luís Saorín, M. Contero, M. Alcañiz, D. C. Pérez López, and M. Ortega. 2010. Design and validation of an augmented book for spatial abilities development in engineering students. *Computers & Graphics* 34 (1):77–91. doi: 10.1016/j.cag.2009.11.003.

Montello, D. R., and H. L. Pick. 1993. Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior* 25 (3):457–84. doi: 10.1177/0013916593253002.

Montello, D. R., K. L. Lovelace, R. G. Golledge, and C. M. Self. 1999. Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers* 89 (3):515–34. doi: 10.1111/0004-5608.00160.

Ooms, K., P. D. Maeyer, and V. Fack. 2014. Study of the attentive behavior of novice and expert map users using eye tracking. *Cartography and Geographic Information Science* 41 (1):37–54. doi: 10.1080/15230406.2013.860255.

Ooms, K., P. D. Maeyer, L. Dupont, N. Van der Veken, N. Van de Weghe, and S. Verplaetse. 2015. Education in cartography: What is the status of young people's map-reading skills? *Cartography and Geographic Information Science* 43 (2):1–20.

Salvucci, D. D., and J. R. Anderson. 1998. Tracing eye movement protocols with cognitive process models. In *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society*, eds. M. A. Gernsbacher and S. J. Derry, 923–8. Hillsdale, NJ: Lawrence Erlbaum Associates.

Self, C. M., and R. G. Golledge. 1994. Sex-related differences in spatial ability: What every geography educator should know. Journal *of Geography* 93 (5):234–43. doi: 10.1080/00221349408979727.

Shimojo, S., C. Simion, E. Shimojo, and C. Scheier. 2003. Gaze bias both reflects and influences preference. *Nature Neuroscience* 6 (12):1317–22. doi: 10.1038/nn1150.

Tolman, E. C. 1948. Cognitive maps in rats and men. *Psychological Review* 55 (4):189–208. doi: 10.1037/h0061626.

Tsai, M.-J., H.-T. Hou, M.-L. Lai, W.-Y. Liu, and F.-Y. Yang. 2012. Visual attention for solving multiple-choice science problem: An eye-tracking analysis. *Computers & Education* 58 (1):375–85. doi: 10.1016/j.compedu.2011.07.012.

Wang, H., Y. Chen, and C. Lin. 2014. The learning benefits of using eye trackers to enhance the geospatial abilities of elementary school students: Learning benefits of using eye trackers in geospatial abilities. *British Journal of Educational Technology* 45 (2):340–55. doi: 10.1111/bjet.12011.

Ward, S. L., N. Newcombe, and W. F. Overton. 1986. Turn left at the church, or three miles North. A study of direction giving and sex differences. *Environment and Behavior* 18 (2):192–213. doi: 10.1177/0013916586182003.

Wu, M.-Y. 2004. The study of spatial ability learning for fourth graders: Take solid geometric net as an example. Master thesis., National Taipei University of Education.