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SCAFFOLDING SPATIAL PROBLEM SOLVING IN SCIENCE: GUIDELINES DERIVED FROM THEORY AND RESEARCH

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Abstract

Spatial skills have been recognized as a predictor of achievement and performance in Science disciplines. These skills are expressed through different problem-solving strategies, depending on content, students' characteristics and provided representations. The purpose of this article is to identify critical issues in scaffolding students' spatial problem solving in science, based on the development of alternative strategies through the interaction with multiple representations. Perceiving representations as tools, their beneficial effect on problem-solving is interpreted through the mediated action theory. Taking into account cognitive and developmental theories and research findings, a framework that includes critical dimensions, like representations' characteristics and students' age, is proposed. Finally, we consider the possible potential of geospatial representations for introducing students in science problem-solving and conclude by examining implications for research.

Keywords*: spatial skills, problem-solving, alternative strategies, geospatial representations*

1. INTRODUCTION

An increasing number of research papers suggest the correlation between success in science and spatial ability. Through three studies, Kozhevnikov et al. (2007) associate spatial ability with effective physics problem solving and interpretation of diagrams. Ozdemir (2010) concludes the positive correlation between spatial ability and mineralogy learning. Pribyl and Bodner (1987) support the importance of spatial ability in organic chemistry performance, and in particular in problem solving skills. Wai, Lubinski and Benbow (2009) show the key role of spatial ability in later science occupation and expertise. In a special edition of the National Research Council (NRC, 2006), the importance of spatial thinking in education is indicated and examples of its application in history of science are mentioned.

These findings provide evidence for the possible usefulness of specialized interventions with the aim of improving spatial skills, in order to avoid exclusion from student participation in science disciplines. Spatial ability malleability research was summarized in a meta-analysis which included 217 studies (Uttal et al. 2013). Reviewed research included a vast variety of interventions: repeated practice on spatial ability tests, playing video games, origami lessons, map reading, hockey training and others. The results of the meta-analysis show that spatial ability is moderately malleable, training effects were stable during time and training was transferred to other spatial tasks that were not directly trained.

But what kind of spatial ability interventions are the ones that could provide maximum benefit for science performance? By utilizing research results and learning theories, this paper aims to provide a model that could be used as a framework for research and enhancement interventions in spatial aspects of scientific problem solving. The sequence begins with the use of multiple representations, which processed through multiple codings will lead to the development and familiarization with multiple strategies. The above mentioned model draws on the Vygotskian mediated action theory (Vygotsky 1997). Further guidelines are deduced and specified through adaptations of the Multimedia Learning Theory and research findings concerning developmental factors that affect interaction with different types of representations.

2. SPATIAL PROBLEM-SOLVING STRATEGIES

Spatial problem-solving activities are approached by utilizing alternative strategies, depending on their presentation and the subject's particular characteristics (Nistal, et al., 2009; Harle and Towns, 2011; Ramful, Lowrie, and Logan, 2016). An effective approach in one spatial ability dimension is not necessarily effective in every other one. But even among activities of the same dimension, the implementation of alternative strategies could produce better results (Ramful at al., 2017). Specifically in science problem solving, a differentiation between more spatial-imagistic and spatial-analytic strategies is suggested (Stieff, Hegarty and Dixon 2010; Stief, et al., 2010). Characteristic features of spatial-imagistic strategies are processes related to mental rotation, perspective taking and spatial visualization. These abilities are the ones usually measured by classical spatial ability tests. On the other hand, spatial-analytic strategies involve the implementation of disciplinary rules, domain specific representations, algorithms and heuristics (Stieff, 2013).

Novice problem solvers tend to rely on spatial imagistic strategies. As content knowledge and expertise increase, spatial analytic strategies gain ground (Stieff et al., 2010; Stieff 2013). Both strategies solely have limitations, spatial-imagistic strategies can not be implemented solely in complex content-related problems and spatial analytic strategies can often be implemented in a restricted range of subject-related problems. Consequently, effective spatial problem solving in science disciplines requires strategy switching, combination and cooperation.

Despite the effectiveness of multiple strategies in problem solving, learners tend to implement single strategies (Tabachneck, Koedinger and Nathan 1994; Cox and Brna 1995). One of the factors that could encourage learners to utilize multiple strategies could be the interaction with multiple representations. Ainsworth's (1999) functional taxonomy of multiple representations includes three main functions: complementation, constrainment and construction. The interaction between representations and problem-solving strategies is proposed, based on the complementary role of representations on tasks and strategies, but also by taking in consideration learner differences. Nistal et al. (2009) point out that problem solving strategies are connected both to the characteristics of the used representations as well as students' characteristics when interacting with representations.

Despite the obvious usefulness of multiple representations in the presentation of all aspects of scientific concepts and their interaction with alternative strategies in science problem solving, research results are divided equally between those that find positive learning results in the provision of more than one representation and the ones that don't (Ainsworth, 2006). Since interaction with multiple representations in science is inevitable for both content knowledge and presentation, as well as for activating related problem solving strategies, factors that prevent the effective manipulation of multiple representations have to be recognized.

One of the proposed factors for the not always beneficial use of multiple representations is the so called representation dilemma, according to which students have to learn new content using new representations they do not yet fully understand (Rau, 2016). Additionally learners have to understand the encoding and the relationship between the representation and the represented domain (Ainsworth, 2006). Stull, Gainer, Padalkar and Hegarty (2016) indicate the high cognitive load that relates to the use of multiple spatial representations. The example they use is the manipulation of alternative representations of organic molecules. Standard procedures include the overloading of limited cognitive capacities because of the complicated structure of many molecules, conversion of 3-D entities in two-dimensional printed diagrams and translation between different diagrams involving mental transformations like rotation and multiple perspective processing. It becomes obvious that a novice learner in a specific STEM domain encounters multiple challenges when involved in disciplinary problem solving.

Apart from the demanding cognitive procedure of content knowledge and understanding, learners are expected to be able to implement complex interactions between multiple representations and operate abstract spatial processing. Through this description, the beneficial role of higher spatial ability levels becomes apparent. The implementation of more effective spatial processing, will lead to cognitive load relief (Sweller, 2011), directing an increasing amount of cognitive resources towards content understanding and representational interaction.

In order to design interventions that will promote the above mentioned polymorphism of strategies, the juxtaposition of stimuli is not enough. Attention should be given both to the choice of these stimuli but also to their utilization in activities useful for the development of spatial reasoning in science problem solving. The theoretical background for such interventions could be based on two well established learning theories, the mediated action theory and the multimedia learning theory.

3. MEDIATED ACTION THEORY

Uttal (2000) in a theoretical documentation of the usefulness of maps in improving spatial reasoning, reviews a series of surveys that show the effect of symbolic representation on the way children think about information. There are examples where knowledge of reading and writing has been shown to improve the use of syntactic and grammar, and the knowledge of mathematical symbols brings information to the forefront of consciousness, which otherwise would not be obvious and would remain inaccessible. Uttal analyzes the effect that maps have on children, moving on to an understanding of space independent of the constraints attached to direct natural experience, leading them to a more abstract and spatial relationship-oriented approach. He concludes that maps could be used as thinking tools for spatial reasoning, which after their internalization will contribute to the comprehension and processing of spatial data, even when students are not engaged in map activities.

The tool internalization process in the above reasoning, embraces characteristics from the Cultural-historical activity theory which is based on Vygotsky's learning theories. Usually the enculturating role of visualizations is highlighted when referring to Vygotsky's Theories in educational research. According to this perspective participating in community practices and by observing more knowledgeable persons, students familiarize and induce ways of thinking common in scientific communities (Lave and Wenger, 1991; Reiser and Tabak 2014). A key-term in this context is the zone of proximal development (ZPD), which describes the potential learning that can occur while transacting during problem solving activities with experts, adults and more knowledgeable peers (Vygotsky, 1978). Through this procedure, students' participation in discipline discourse and construction of knowledge is facilitated (Airey and Linder, 2009; Rau, 2016). This kind of interactions are mainly discipline related and familiarization with disciplinary tasks have been tested successfully as mediation factors for spatial thinking (Stieff 2007; Hambrick et al., 2012; Stieff, Lira, and De Sutter, 2014). On the other hand, it is assumed that training in very specific tasks, like spatial tests or strictly disciplinary tasks will have a low degree of transfer (Uttal and Cohen, 2012) in other tasks different from the trained ones.

A more generic mechanism for spatial skill improvement in spatial problem solving could be based on other aspects of the activity theory. Three generations of activity theory have been identified by Engeström (2001). The first-generation is based on Vygotsky's mediated action theory. The second-generation activity theory is mainly based on Leontiev' s work and emphasizes on the sociocultural elements of human activity. According to the third-generation activity theory, researchers play a participatory role and intervene in the participants' activities.

Taking in consideration the intrapersonal nature of spatial mental processing, the mediated action theory, which is the main method of examining human activity in the first generation activity theory (Yamagata-Lynch, 2010), could be useful in interpreting the mechanisms through which certain representations activate corresponding problem solving strategies. Vygotsky argued that the development of superior cognitive functions requires an activity in which the subject interacts with an object, through the mediation of a tool. The subject is the person who performs the action, the object is the purpose of the action, and the tool / artifact can be a physical object, a symbol, a social contract or an interaction through which the subject performs the action. During this procedure relevant signs, which are factors of behavioural change are developed (Vygotsky 1978, Vygotsky, 1997).

Thus, e.g., when using a hammer to nail a nail on the wall, the subject uses the hammer as a tool, which mediates between him or her and nailing, which is the object. But as soon as the subject is familiar with the use of the hammer, he recognizes new possibilities in its use, different from its primary use. The hammer is no longer a tool that is restricted to a single activity, but an object of thought, a sign, with which not only other actions can be done, but elements of its manipulation can also be transferred in the use of other tools or even in the creation of new tools that best meet the subject's needs in performing specific actions. The above procedure for converting a tool to a sign is called internalization. In this process, external actions and experiences are transformed through meaningful activities into behavioral factors, and the individual becomes able to achieve superior cognitive functions (Vygotsky, 1997, Yamagata-Lynch, 2010).

By following the mediated action terminology in the case of spatial problem-solving enhancement interventions, students are subjects, object is the spatial activity that should be completed and mediating tools are the representations (graphs, photographs, maps, texts etc.) of the information provided to achieve problem-solving. The diversity of data visualization, through the purpose they perform within the activity, become a variety of available tools, which through their mediating action will be transformed into signs, related to the particular characteristics of the subject-representation interaction. The internalization of these tools will lead to enhancement of spatial problem solving strategies because elements of manipulation of maps, photographs, and other alternative representations, should be transformed and applied to mental spatial processes even if maps, photographs, etc. are not used.

4. MULTIMEDIA LEARNING THEORY

The mediated action theory provides a theoretical framework for spatial reasoning enhancement activities, but the representation-selection and task-design procedure can be further specified through the conclusions of the cognitive multimedia learning theory. The basic principle of the multimedia learning asserts that pupil's knowledge and understanding is promoted through the blended presentation of words with images (Mayer, 2003). The three assumptions are the dual coding assumption, the limited capacity assumption and the active learning assumption.

According to the dual channel assumption, individuals possess two distinct coding systems, one for visual and one for verbal stimuli. Thus, photographs, drawings, shapes are processed through the visual channel while texts and oral narratives are processed through the verbal channel. This assumption is based on the research done by Paivio (Clark and Paivio, 1991) and Baddeley (1992). Paivio's dual coding theory, postulates the existence of two independent memory and processing codings: one of words and one of images. The Baddeley model (Baddeley, 2000) consists of four components: the phonological loop, through which the storage and evocation of verbal and acoustic information is accomplished, the visuospatial sketchpad, which is responsible for the manipulation and processing of visual and spatial information, the central executive, which is responsible for strategy selection and data integration and finally the Episodic Buffer, which plays a combined role, using a polymorphic code which derives features from both the verbal and the visuospatial code.

The limited capacity assumption argues that the volume of processed information that can be channeled into each of the two channels, visual and verbal, is limited. The restrictive factor in this case is working memory, a short-term memory which is activated for information used to complete an activity, such as problem solving (Reed, 2006). Behavioral, neuropsychological and neuroimaging research indicates the discrete existence of a visuospatial and a verbal working memory (Smith, Jonides, Marshuetz, and Koeppe, 1998). Thus, it is understood that if a relatively large amount of information-data is required in order to understand a phenomenon or to solve a problem, it is preferable to direct them through the two processing channels mentioned above rather through a single coding channel.

Increased amounts of spatial working-memory resources have been associated with higher spatial ability levels (Miyake and Shah, 1985). Spatial working memory seems to play an important role in mental rotation activities. In these activities the subject has to imagine a two or three dimensional object' s appearance after it has been turned around a point by a certain angle (Shepard and Metzler, 1971). While involved in mental rotation activities, mental images developed by subjects with low spatial ability fall apart and they are limited to process only a part of the object, by implementing piecemeal strategies in contrast to high spatials who implement holistic strategies (Just and Carpenter, 1985; Khooshabeh and Hegarty, 2010).

The third assumption concerns active learning. According to Mayer (2003), active learning occurs when presented words and pictures are organized into coherent verbal and pictorial representations with one another and with prior knowledge resulting to a learning that can be transferred to problem-solving. The above mentioned mediated action theory and the tool internalization process could provide useful guidelines on the problem-solving transfer mechanism.

Several researchers propose that the visual coding channel is not homogeneous, but that it is distinguished in two distinct and independent channels. Gray and Pitta (1999) report two types of visualizations that emerged from elementary students, one more schematic, skeletal and symbolic, and another more detailed, colorful, pictorial that was identified with real objects and specific scenes. Similar are the results of Hegarty and Kozhevnikov (1999), which also distinguish between schematic and pictorial visualizations. Blajenkova, Kozhevnikov and Motes (2006) support the existence of two distinct visualization systems, one of the space and one of the objects, which codify and process the information in a different way. Spatial visualization refers to more subtractive representations of the spatial relations of objects and their parts, their location in space, the movement of shapes and their spatial transformations, while the visualization of objects refers to the representation of the real image of an object, its exact size, color, etc. Kozhevnikov, Kosslyn and Shephard (2005) concluded that users of spatial visualizations, process the images analytically in successive stages and piecemeal while the users of object visualization encode and process the image holistically as a single sensory entity.

Summing up, the multimedia learning theory supports improving learning when the student comes into contact with the subject through two channels, both verbal and visual. This is because of the finite capacity of the two channels. Part of the Information that could not be processed through one channel, e.g., the verbal because of its finite capacity, is now directed for processing by the visual channel. However, a large number of studies suggest that the visual channel is not homogeneous, but that it is distinguished in two independent channels, which in general could be called schematic and pictorial channels. The first is distinguished by the deduction and presentation of spatial and metrical relations between the various elements of representation (geometric shapes, charts), while the second concerns the realistic representation of the object to be represented (pictures, paintings, videos). By adapting the multimedia learning theory to the aforementioned splitting of the visual in two independent channels, the pictorial and the schematic, the following assumptions could be deduced:

- In the same way that processable information is increased by splitting it into two channels (optical-verbal), it could be further increased by distributing it into three channels (verbal-schematic-pictorial).
- The increased amount of processable information in less time will provide the scope for efficient enhancement of specific processing skills with short-term didactic interventions.
- The adaptation of the three different representation channels with each other and with previous knowledge could enrich the arsenal of alternative strategies associated with these channels, leading to more effective problem solving. The central executive will enrich student choices in alternative strategies, and the Episodic Buffer will use an enhanced polymorphic code to derive features from all three channels (verbal, schematic, pictorial). Investigation for correlations between the two visual coding channels (schematic,pictorial) and the aforementioned strategy differentiation in science problem solving (spatial-analytic, spatial-imagistic) would be useful. In both cases the problem context must be described through the verbal channel, either in the form of question expression or verbal guidance.

Following the mediated action terminology, if the intervention activity involves the combined use of these tools-representations, we could expect extraction of data not from individual tools but from their combined application. The internalized tools that are acquired through the above described procedure will develop into signs, providing a scaffolding for later introduction in science problem solving activities, with a gradual increase in visual and content complexity.

5. DEVELOPMENTAL CONSIDERATIONS

In order to find the suited embedded content included in the enhancement activities, subjects' age is a crucial factor. Studies show the decline of children's attitude and interest towards science from the point of entry to secondary school, which are attributed to children's perceived difficulty of the subjects and the failure to perceive relevance to their everyday life (Osborne, Simon, and Collins, 2003). Since spatial thinking is considered a major factor for performance enhancement in science subjects, it could be assumed that relevant enhancement interventions could be beneficial before or at the beginning of the transition to secondary school, before students are excluded from engagement in science because of their interest and attitude decline.

Sorby and Baartmans (2000) developed successful ten-week systematic interventions, aiming to improve engineering freshmens' spatial skills. The spatial skills were selected as the most suitable for success in engineering graphic courses and included topics like isometric and orthographic sketching, pattern development and cross-sections of solids. Assumingly at this age students should have achieved some level of domain-specific knowledge, through which spatial analytic strategies are playing an increasingly important role, gradually replacing generic spatial-imagistic ones which are stronger related with the subject's spatial skills (Stieff 2007; Hambrick et al., 2012; Stieff et al., 2014). Another reason for the application of interventions before the transition to secondary school, is the relatively low content knowledge level across subjects, a fact that drives students to use more generic spatial-imagistic strategies in problem solving than content mediated spatial analytic strategies. Even if experts tend to increasingly use spatial analytic strategies, it is profound that at a young age because of their content knowledge limitations they initially relied on spatial imagistic strategies which are closely related to spatial thinking skills. Furthermore this initial application of spatial imagistic strategies must have been successful, considering experts' non declining interest and attitudes towards science and their sustained engagement with scientific activity.

Some obstacles may exist in the implementation of multiple representations at this age. According to the Piagetian development theory the age around 11-12 is when the formal operational stage can begin (Piaget, 1966; Ahmad, Batool. Sittar, and Malik, 2016). In this stage successful learning of abstract science content is possible, using appropriate representations like models and graphs. Findings show that these kind of representations, which are abstract by nature and are correlated with non-directly observable science content, cannot be handled successfully by learners who have not reached the formal operational stage (Moore and Slisko, 2017; Dickerson, Penick, Dawkins and Van Sickle, 2007; Goodstein and Howe, 1978).

At this point the problem that occurs is that without the use of these symbolic representations, the available materials, which could be used in pre secondary interventions, are limited and the above analyzed principles of the use of multiple representations for spatial problem solving enhancement cannot be implemented. A possible solution may be provided, through the use of maps and geospatial representations.

6. MAPS AND GEOSPATIAL REPRESENTATIONS

There is strong evidence that children can use maps to complete tasks even in preschool and early elementary grades (Uttal and Wellman, 1989; Uttal, Fisher and Taylor, 2006; Huttenlocher, Vasilyeva, Newcombe and Duffy, 2008; Yuan, Uttal and Gentner, 2017). This possible early familiarization with maps may be a result of the primacy of the direct experience with space and the representational familiarity of certain representational means used in maps, eg. the schematization of an aerial view (Davies and Uttal, 2007).

Concerning the representation dilemma, this early ability to use maps may be proven beneficial. The two aforementioned hindering factors are the simultaneous use of unfamiliar representations in an unfamiliar content. The use of representations could be scaffolded with maps, which have been proven usable even by preschool children, interacting with a relative familiar content, like known landscapes or home neighborhood. The inherently interdisciplinary nature of geography (Baerwald, 2010), could provide opportunities for disciplinary mediated processing, derived from a variety of disciplines.

Apart from maps, geospatial technologies could provide a number of alternative map-based representations. There are demonstrations that 10 year old children can use maps, global positioning systems (GPS) and geographic information systems (GIS) combinatorially (Lambrinos and Asiklari, 2014). Geospatial technologies like GPS, GIS, virtual globes and virtual tours have been investigated successfully in spatial thinking enhancement interventions mostly with university (Lee and Bednarz, 2009: Kim and Bednarz, 2013: Kurtuluş, 2013) and secondary students (Patterson, 2007). Additionally, to the promising spatial enhancement potentials of these representations, they also provide options that meet the aforementioned guidelines of the adapted multimedia learning theory, by using schematic (maps, GIS), pictorial (virtual tours, virtual globes) and verbal codings (verbal task and informative texts).

An interesting fact is that relevant multi-representational learning applications using geospatial technologies in late elementary and early secondary grades have been implemented for local history and heritage learning, a subject not strictly related with science. The aims of research done in this domain are usually learning results, usability of technology and user experience. Below, three characteristic examples of these applications will be described briefly. Apart from the multi-representational perspective, all three of them are related with local history and heritage, and are implemented outdoors.

Fourth, fifth and sixth graders used geospatial technologies in a treasure hunt in which they connected their position in the physical environment with their position in a map and the coordinates of a GPS unit (Lambrinos and Asiklari, 2014). Students produced a new map with georeferenced points of interest, accompanied by photos and texts describing local points of interest. Seventh graders in Portugal developed a georeferenced historical route using virtual globes, satellite imagery in combination with photographs and texts (Magro, de Carvalho and Marcelino, 2014). Students aged between 12-14 in Chile, used mobile pedestrian navigation systems and augmented reality applications, in a mobile learning context. A variety of educational resources were incorporated in the application including photographs, informative texts and digital maps (Joo-Nagata, Abad, Giner and García-Peñalvo, 2017). The learning objective was knowledge acquisition about cultural heritage in Santiago.

Similar scavenger hunt and outdoor activities seem to implement elements of the above mentioned guidelines, providing students the opportunity to interact with a variety of representations. Subjects concerning the local community, with which students may have an increased familiarity, may be proven beneficial for overcoming the above described representational dilemma. Because of time restrictions a possible alternative to outdoor activities, may be provided through virtual tours or virtual reality environments.

CONCLUSIONS

This paper focused on three interrelated components that affect scaffolding student's spatial problem solving in science: Individual characteristics, types of representations and strategy choice. Higher levels of spatial ability have been associated with enhanced performance in science domains. In terms of science problem-solving, spatial skills are mainly implemented with spatial imagistic rather than content mediated, spatial-analytic strategies.

Science problem-solving usually demands combinatorial strategy implementation, consequently scaffolding interventions should trigger the use of a variety of strategies. Apart from individual characteristics, strategy choice is affected by available representations, assumingly multiple representations could be associated with the combinatorial implementation of a variety of strategies. The representation-strategy choice interaction mechanism could be based on the perception of representations as problem-solving tools and the tool internalization mechanism derived from the mediated action theory.

The benefits of multiple representations in enhancing spatial problem solving in science are accompanied by demanding cognitive procedures like the simultaneous processing of representations and new content, the demanding implementation of spatial thinking and working memory load. The adapted multimedia learning theory provides cognitive load-reducing solutions, through the splitting of the visual coding channel to two distinct schematic and pictorial channels. Possible correlations between different types of representations and process codings could make problem solving with multiple representations manageable by more students.

Taking into account attitudes and interest decline after the transition to secondary school, but also the significant role of spatial processing before content knowledge starts to play an increasing mediating role, late elementary grades are proposed as the most fitting for scaffolding interventions. In order to overcome developmental restrictions concerning processing of abstract science representations , maps and geospatial technologies are suggested as a promising choice for the introduction of pre- secondary students in the processing of abstract scientific representations.

Further research could specify possible correlations between strategy implementation (spatial-imagistic, spatial-analytic), process coding of representations (pictorial, schematic) and individual characteristics (level of spatial ability, content knowledge, age). Findings in this domain could result in a concrete scaffolding intervention process, which could either be embodied across school subjects or included in a specific discipline.

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