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The movement in spatial thinking in STEM-subjects

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This research project relates to the core of spatial ability linking to the STEM-subjects. Well-developed spatial abilities may lead to better comprehension of scientific and technical matters and to solving current real-world issues by thinking spatially in a variety of ways. The purpose of the study is the application of spatial abilities in the sense of spatial thinking as an entirety, which interacts in a broad way in the fields of science, mathematics, physics and technology. We have developed a new model of the extended Spatial Thinking for STEM, within we have underlined the movement as an essential element of spatial thinking. The various perspectives on movement in spatial thinking are combining elements, which show the interrelation between the subjects of STEM. This is described by selected examples.

Keywords: Experience and space, movement, visual perception, spatial thinking, problem solving.

Spatial thinking – the application of spatial abilities

Spatial thinking as an entire ability

Spatial thinking is the mental process of representing, analyzing, drawing inferences from spatial relations [...] between objects [...] or relations within objects, [...] analyzing spatial relations and transforming spatial relations. (Uttal et al., 2013, p. 367)

Spatial thinking, the “visual processing and spatial cognition” (McGrew, 2009; p. 5; Buckley et al., 2019, p. 168) is a complex ability, which reveal the various spatial thinking processes. They are used individually and are changed within the solving processes of tasks (Barratt, 1953; Just & Carpenter; 1985; Schultz, 1991).

One of the first researchers, who named various aspects of spatial thinking, is the British scientist and mathematician Francis Galton.

Much instruction on these matters can be derived from those who possess the power of what is called the visualising faculty, in a high degree. The objects of their memory are conspicuous images; they can retain them for a long time before the eye of their mind, they can dismiss or change them at will, and they can, if they please, subject them to careful examination from every side. (Galton, 1879, pp. 158)

In this description, Galton implied three steps in the process of spatial thinking: the perception, the memory as the possibility to retain and to retrieve a recognized object and the imagining and operating with spatial pictures. This indicates an entire view on spatial thinking, as we can find also in novel definitions, for example the visual and spatial capacity of the intelligence is “the ability to generate, store, retrieve and transform visual images and sensations” (McGrew, 2009, p. 5). Furthermore, McGrew (2009) relates in his description to the perception and imagination of shapes, images and spatial orientation of objects, which change their shapes and positions in space by movement. Also

in the actual research, spatial memory is a central element in spatial thinking, which is expressed in the following explanation “largely determined by the capacity to represent and manipulate mental information (spatial cognition) and to hold sufficient amounts of pertinent information (working memory)” (Buckley et al., 2019, p. 166).

Thinking about and with space in STEM

Spatial thinking includes thinking about space and thinking with space (Hegarty & Stull, 2012). The former means the experience in real space, in large-scale environment in which you can only see part of the whole at the same time. Further, it means the mental operating with real and imagined objects in space, in the small-scale. Thinking with space relates to the use of spatial objects and spatial mental processes for the imagining of non-spatial contents, for example the use of symbols and of graphs in coordinate systems, the representation of abstract contents in diagrams and the structure of terms (Malle, 1993).

Spatial thinking needs to be promoted for problem solving in the subjects of STEM. Many studies reveal that students have more success in attending courses and finishing their study on the academic level when they have a good developed ability to think spatially. Also in the further professional working, they can arrive higher aims. (Uttal & Cohen, 2012; Sorby et al., 2018)

Wai et al. (2009) highlight the interaction of the three abilities, spatial ability, mathematical ability and verbal ability. This necessitates a change in mindset in favour of spatial thinking for the curricula. Young adults with well-developed spatial abilities seem to handle better images and shapes in the imagination than those who think in verbal and numerical symbols (Wai et al., 2009; Mix et al., 2016). Probandes with less-developed spatial abilities and well-developed verbal skills try to solve mathematical problems with verbal description, while others prefer a spatial representation in the problem solving (Fennema & Tartre, 1985). This relates to the usual structure of the logical thinking: a deductive and verbal process and a structured, global, intuitive spatial and inductive process (Tartre, 1990). Even though “reasoning thinking” with verbal and analytical processes is sometimes elevated above the spatial perception and imagination, spatial thinking is the core of thinking (Duffy et al., 2018, p. 273). Only the interaction of the two mental areas, the abilities of the spatial and of the rational thinking, leads to the expected success in STEM-subjects (Duffy et al., 2018; Sorby, et al. 2018).

Studies reveal that a higher spatial ability combined with a visual working memory supports the success in academic learning and the understanding of subject contents in the beginning of study. However, on a higher level specialist knowledge and experience are more used and successful in problem solving in STEM-subjects. (Uttal & Cohen, 2012; Duffy et al., 2018; Xie et al., 2020)

Spatial thinking extended to problem solving in STEM

In the following, we describe the development of a new model in Spatial Thinking for STEM. The aim of this attempt should be the application of spatial mental processes in mathematical, physical and technical issues.

From visual perception and spatial imagination to further reasoning

Previous research has primarily focused on exploring visual perception (Vernon, 1962; Frostig et al., 1972) and spatial ability (Thurstone, 1938; Linn & Petersen, 1985; Maier, 1994) as two distinct pillars of spatial thinking. Most models on spatial thinking and spatial abilities, and the related tasks have concentrated on artificial, theoretical situations in psychometric tests, and they have rarely considered scientific subject contents. To fill this research gap, there is constructed a model combining neurological findings of visual perception and spatial ability with the application on real problem solving in STEM-subjects. Spatial thinking and acting includes the two areas, visual perception and spatial ability.

Visual perception is the anatomical and neuronal process from the sensory stimulus to the cortical cognition. It is the ability for seeing the world around us recognizing and identifying objects and situations. Other sensory stimuli, especially motoric and auditory ones complete the visual perception, which is the most involved in spatial ability (Nänni, 2009). From the psychological literature (Vernon, 1962; Bak, 2020) and from neurological research (Burgess, 2014) we outline three fundamental components of visual perception: the perceiving of objects, movements and depths.

Spatial ability is the capacity to operate mentally with the images arising from visual perception, for instance, transforming, rotating, cutting and combining them. Sensory impressions are processed and reorganized mentally. We have to work actively on these mental images. (Thurstone, 1938; Maier, 1994)

In addition to the combination of visual perception and spatial ability (Maresch, 2020), a further component is necessary. This relates to the applying of spatial processes in spatial and non-spatial contents, including a higher level of thinking for arguing, reasoning and problem solving on abstract mathematical contents. This level includes expedient analyzing and creating individual solving steps (Figure 1). The “Movable Thinking” (Roth, 2005) in mathematical and geometrical contents can be seen as a further aspect of the higher spatial thinking. It is the capacity to find a movement and movable parts inside a geometrical constellation and to use them for arguing and proving.

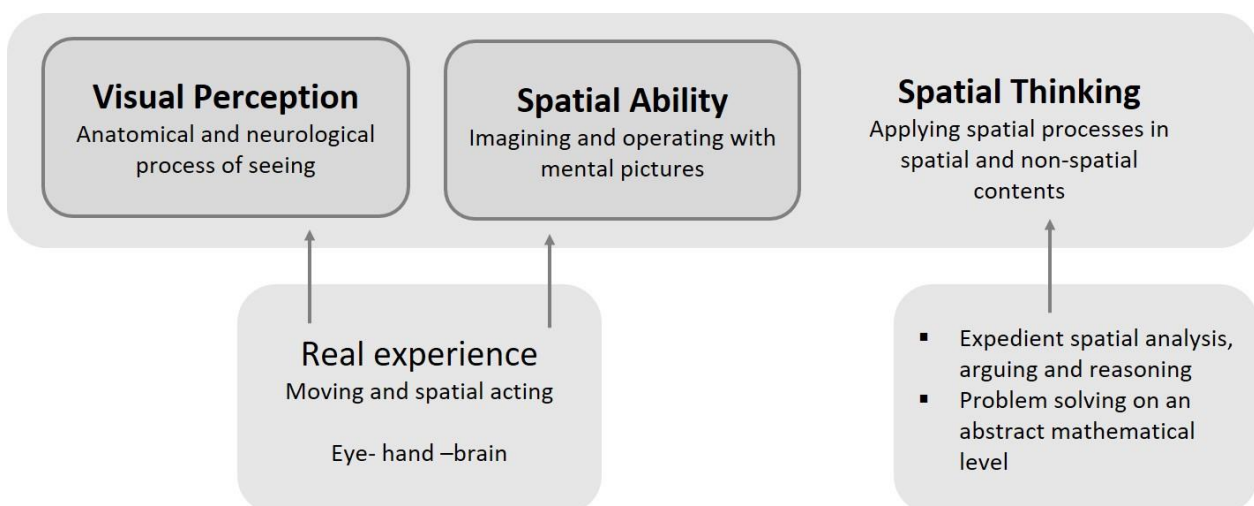


Figure 1: Spatial Thinking in STEM

The extended model of Spatial Thinking in STEM

The model is composed of six fundamental and two overarching facets (Figure 2). They relate to contents of space and take place on every level of spatial thinking, namely the visual perception, the spatial imagining and the expedient thinking.

The extended model of Spatial Thinking in STEM			
Overarching facets		Fundamental facets	Structure of each facet
Spatial problem solving	Spatial memory	<ul style="list-style-type: none"> ▪ The nature of objects in the focus ▪ Position of objects in space ▪ Change of object properties in space ▪ Real and potential object movement ▪ Decomposition and combination of objects ▪ Spatial orientation in real and mental space 	Perception
			Imagination
			Expedient mental arguing
			Static and dynamic component

Figure 2: The facets of Spatial Thinking

The nature of objects in the focus relates to the comprehending of a constellation as a whole, from which single objects or parts are distinguished. The objects should be recognized in their relevant properties as constancies for identifying them and removing them from the background. Referring to mathematics, this facet includes arguing with geometrical properties, such as invariances, orthogonality and parallelism.

The position of objects in space deals with the perceiving and imagining of the location and position of one or more objects in a spatial constellation, in relation together and to the viewer. For example, it includes the spatial relations of elements of areas and solids, such as the relation between lines, edges, and angles. The combination between the geometrical imagination and the algebraic representation of straights and planes in a metric space requires this facet using coordinate systems.

The change of object properties in space is the changing of objects and parts of them through mirroring, rotating, shifting and scaling. This happens by the imagining of movements to recognize the changing process between the initial and the final state of the object. As an example, we can name the varying aspect of variable quantities.

The real and potential object movement relates to a real movement in space and a possible movement in a mechanical configuration with movable parts, not to a fictive movement in a mathematical constellation. This facet has a concrete reference to various fields of physics and technology, while it is related indirectly to mathematics via the similarities with the facet of the change of object properties. For imagining the deflection of a moving object, e. g. a rolling ball (Kozhevnikov et al., 2007) or a moving charged particle in a homogeneous magnetic field (Fulmer & Fulmer, 2014), we should be able to follow mentally the path of the movement.

The facet of decomposition and combination of objects involves breaking down an object or a configuration into parts and combining the parts into a whole object or a new configuration through

Boolean operations. In a further sense, it relates also to the structuring of terms and the imagining of fractions, as a part of the whole.

The spatial orientation in real and mental space is about the orientation of a person in the real space and in the mental imagination, whereby it is necessary to put themselves into the space. By changing the perspective, an object or a constellation of objects can be seen from different angles. Referring to physics, for instance, this facet is important for the imagination of movements in astronomy (Cole et al., 2018). As a viewer from different points on earth, as well as from outside the earth we see different movements, which we have to combine for understanding the interrelation, for example the apparent movement of the sun and the real movement of the earth.

The spatial problem solving and the spatial memory flow in into all fundamental facets, in understanding the task, in mental and concrete processing of solving the task, in assessing the solution steps and in finding further possible solutions.

The movement as a central element of spatial thinking

Movement, as the change in location and position of an object in space and as the change of properties of an object, as well as the movability as a possibility for changing, pervades the spatial thinking as a whole. Movement appears in various ways, as imagining and anticipating a sequence of movements, as a mental process of changing an image or as a mental process for solving problems. Based on the real movement and orientation in the space to explore it and on feeling the movement of one's own body occurs the transfer of perception into the imagination. (Stückrath, 1955; Piaget & Inhelder, 1971; Glück et al., 2005; Wolbers & Hegarty, 2010)

We have found four perspectives on movement, which are important in the imagining of mathematical, physical, technological and scientific contents:

- the movement which can actually be experienced in space and which is comprehensible in the imagination,
- the potential movement of a movable part of a mechanical configuration, for example the movement of gearwheels, screws and pulleys,
- the mental movement of an entire object to change its properties,
- the mental movement to change single parts in a mathematical constellation as an internal displacement, for example folding a solid by its surface. This relates also to the movement which is applied in abstract mathematical and geometrical contents, as movable thinking.

In the following, we present two examples, one for the spatial imagination of potential movement in a mechanical constellation (Thurstone, 1938) and one for the spatial imagination of real movement in an astronomical context.

The movement in a mechanical configuration

A rightwing screw engages a gearwheel in the signed direction. The gearwheel rotates on a fix axis. We have to imagine spatially how the rotating movement of the rod is combined with the translation movement. In which direction does the gear rotate when the threaded rod engages the gear in the

indicated sense of rotation? In which direction does the gear move, when the worm is put on the rod inversely, from the right side to the left side in this perspective?

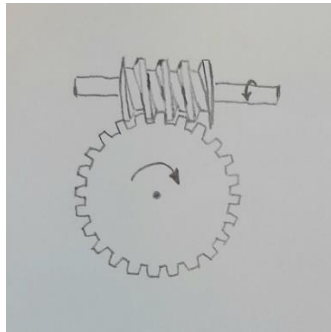


Figure 3: Gearwheel and threaded rod

To solve the task, we fix distinct features in the representation, like the teeth of the gear and the rotating direction of the threaded rod. We can mentally imagine the relation between the rotation and the translation movement of the rod. The picture of a screw turned into a wall can serve as a practical help. When the worm is put inversely on the rod the spatial relations are conserved and the direction of each spiral is unchanged, as the thread remains a right-hand thread. The spatial thinking relates to the recognition of the spatial relation between the parts of configuration and their movement.

The movement in an astronomical task

A further example to improve the imagination of movement in science deals with the path of the sun, seen from diverse places on the earth. The content of the task refers to the daily rotation of the earth around its axes, whereby other movements and astronomical phenomena are neglected. In which direction do you see the path of the sun in Rome on the North Hemisphere and in Cape Town on the Southern Hemisphere? The absolute cardinal points of the sunrise, the sunset and the peaking of the sun have to be recognized, moreover the reference points to the body of the viewer, such as left or right when looking at the sun. This problem can be seen from the earth at rest, the large scale of experience, and from a fictive point in the universe on the moving earth, the small scale of a geometric model. For simplifying the task, two places outside the tropic are chosen, because otherwise the local and seasonal conditions have to be considered. As spatial approaches can be used: putting oneself into the reference frame through mental change of viewer's position and spatial orientation or considering properties of objects and their relation using geometric quantities in an analytical way. As interesting statements of students for explaining their mental processes can be named the following answers: "I have thought about the earth as a sphere with one half in the shadow", "The earth rotates in certain points in the direction of sun and in others away from it", "I have mentally imagined a person living near Cape Town." (Zöggeler et al., 2021).

Space and movement in space are the background of spatial thinking.

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