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Spatial Ability
The Phases of Spatial Ability Research

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Abstract. The article first of all illustrates the historic implementation of spatial ability as an aspect of intelligence, then describes the factors which have been identified as constituting spatial ability and its historic genesis, and finally takes a look at the present discussion on the subject of factors of spatial ability, small-scale and large-scale tasks, mental imagery, working memory and problem solving strategies.

Key Words: spatial ability, visualization, spatial perception, spatial relations, mental rotation, spatial orientation, working memory, mental imagery, small-scale and large-scale tasks, dynamic spatial ability.

MSC 2010: 97U50

1. Introduction

Since the turn of the twentieth century researchers have increasingly been convinced that intelligence is not just one dimensional. They tried to identify differing aspects of intelligence and to define it as a multi-dimensional term [4, 6, 10, 14, 42, 44, 46]. Since that time there has been clear evidence that spatial ability differs from verbal ability [6, 21, 44]. This fact was the starting point for spatial ability research.

The most common method for studying spatial ability was the factor analysis, which is a *statistical technique that examines the patterns of correlations among a large number of variables* [18]. This technique tries to observe many variables, has the goal to find out common features among them and wants to reduce the number of constructs, also called *factors*. Mathematically a factor can be seen as a weighted sum of each of the variables and represents an underlying ability [18]. When tests are loading on one of the factors then they are called *markers* for that factor. When we are trying to find out underlying factors of spatial ability, we have to use test batteries which include markers for the factors. For many decades of the twentieth century spatial ability researchers on the one hand were searching for markers for factors and on the other hand used large test batteries with markers to identify underlying factors for spatial abilities and their relations [3, 9, 13, 26, 27, 28, 29, 31, 40, 45] (Table 1).

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Since the end of the twentieth century researchers have assumed that it is not possible to establish one accepted factorial model for spatial ability (e.g., [11]). Investigators identified some possible reasons for that fact (e.g., probands use different strategies for the same tasks; some markers are not testing the factor they should; there is no consistent evidence for the separability of many factors). Because of these perceptions researchers are now focusing on strategies, novel spatial ability dimensions such as dynamic spatial abilities or small-scale and large-scale spatial abilities, individual differences and correlations of spatial ability with mental imagery and working memory.

2. Phases of spatial ability research

Analysing the historic development of the definition of general intelligence and in particular the notion of spatial ability, we can differentiate three phases of spatial ability. First the *Pre-Factorial Phase* from 1904 to 1950, second the *Factorial Phase* from 1950 to 1994 and third the *Post-Factorial Phase* from 1994 until present.

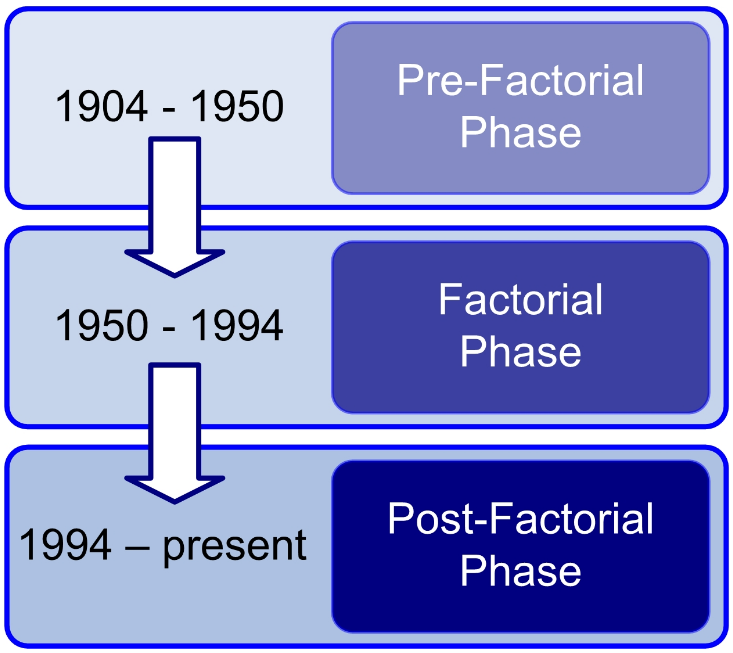

Figure 1: The three phases of spatial ability research

With the beginning of the Pre-Factorial Phase around the year 1900 the focus in many scientific studies was placed on the keyword "intelligence". For the first time definitions, descriptions and models of intelligence were formulated (e.g., [43]). At that time intelligence was described in a very general and one-dimensional manner. Intelligence was defined as the general ability of an individual to grasp new challenges, and adapt her/his thinking to the tasks and conditions of life [43], or also as *the complex and global ability of an individual to act purposefully, to think reasonably and to communicate effectively* ([47], citation translated).

Later researchers began to define intelligence not only as a general, undifferentiated and one-dimensional ability of the individual. They tried to identify differing aspects of intelligence and to define it as a multi-dimensional term [4, 6, 10, 14, 42, 44, 46].

Examples for multi-dimensional models of intelligence of the Pre-Factorial Phase of spatial ability are the following:

- Spearman [42] formulated the two-factor-theory (general factor of intelligence) "g" and further "s" (specific)-factors. He was therefore one of the first scientists to name spatial ability among the specific factors as an aspect of intelligence.
- In his book *"Primary Mental Abilities"* Thurstone [44] defined seven independent aspects of intelligence: space, verbal comprehension, word fluency, reasoning, numbers, perceptual speed and memory.
- Vernon [46] identified spatial abilities as one of altogether ten aspects of intelligence.
- Cattell [4] puts intelligence into three levels of order. The higher the level, the more general are the factors. The six factors of the first level are: verbal, spatial, logical and numerical abilities, flow of speech, and memory. The second level of order is subdivided into fluid and crystalline intelligence. The third level contains historic fluid intelligence and general learning experience.
- Guilford [14] designed a cube to the ratio of $4 \times 5 \times 6$ as a structural model of intelligence, allowing 120 partial abilities to be deduced. With regards to content, two of these partial abilities are figurative and symbolic.
- Gardner [10] determines seven independent factors of intelligence: verbal skills, logical thinking, musical skills, physical-kinesthetic skills, intrapersonal and interpersonal intelligence and spatial abilities.

The multi-dimensional models of intelligence covered a wide range of characteristics. We see models with only two factors [42] but also models with up to 120 partial abilities of intelligence [14]. Nearly all the defined multi-dimensional models of intelligence shared the view that spatial abilities constitute an essential aspect of intelligence.

During the following phase of spatial ability research — the Factorial Phase — the focus was put on a differentiated and mainly psychometric analysis of spatial ability. As spatial ability was defined as an essential aspect of intelligence in all the established models of intelligence, the Factorial Phase, from 1950 to 1994, put emphasis on defining and describing individual factors of spatial ability. Carroll [3], French [9], Guilford [13], Linn/Petersen [26], Lohman [27], Lohman [28], Maier [29], McGee [31], Rost [40], and Thurstone [45] made important contributions to the systematic research of the individual basic factors of spatial ability. The outlined factors of spatial ability are listed in Table 1. The synopsis indicates that the five factors visualization, spatial relation, spatial orientation, spatial perception and mental rotation are the most frequently mentioned aspects of spatial ability (see Table 1) in all the elaborated models. These five factors are described in more detail below.

During the factorial phase further factors of spatial ability were identified by various researchers [3, 28]. An analysis of the studies during the factorial phase shows two trends as regards the number of identified factors: On the one hand it is stated that the number of spatial ability factors could be much higher respectively infinite if the descriptive parameters were differentiated in more detail. *The list is by no means complete because there exist a virtually unlimited number of spatial factors that can be defined* [28, p. 189]. On the other hand the researchers stress the fact that such detail could lead to an interference of factors, diminishing the discriminative power. So it would be better to define only a few factors which are independent from each other.

The Post-Factorial Phase of spatial ability research (since 1994) has been characterized by the understanding that so far selective and independent factors of spatial ability have not been identified. During the Factorial Phase up to ten differing factors of spatial ability

Table 1: Summary: Identified Spatial Ability factors from 1950 to 1994

year (chronological order)	*author*	*visualization*	*spatial relation*	*spatial orientation*	*spatial perception*	*mental rotation*	*further factors*
1950	Thurstone, L.L.	x	x	x			
1951	French, J.W.	x		x			
1956	Guilford, J.P.	x		x			
1977	Rost, D.H.	x		x			
1979	Lohman, D.F.	x	x	x			
1979	McGee, M. G.	x		x			
1985	Linn, M.C., Peterson, A.C.	x			x	x	
1988	Lohmann, D.F.	x		x		x	Flexibility of Closure, Spatial Scanning, Perceptual Speed, Serial Integration, Visual Memory, Kinestethic
1993	Carroll, J. B.	x	x				Closure Speed, Closure Flexibility, Perceptual Speed, Serial Pictoral Integration, Spatial Scanning, Imagery, Length Estimation
1994	Maier, H. P.	x	x	x	x	x	

had been identified. Now there is a trend to reduce them to three to five factors of spatial ability [41]. The current scientific discussion centers round small-scale and large-scale spatial abilities, dynamic spatial abilities, relations to working memory and mental imagery and the awareness that probands use diverging strategies when they are tested in spatial ability. Attention is therefore shifted among others towards identifying possible strategies with which probands sort out spatial ability tasks.

3. Description of spatial ability factors

As mentioned before, most diverse factorial models of spatial ability research had been developed during the Factorial Phase. It is worth noting that specifically the factors visualization, spatial relation, spatial orientation, spatial perception and mental rotation are often designated as independent aspects of spatial ability. These five most frequently factors in literature are presented and described here.

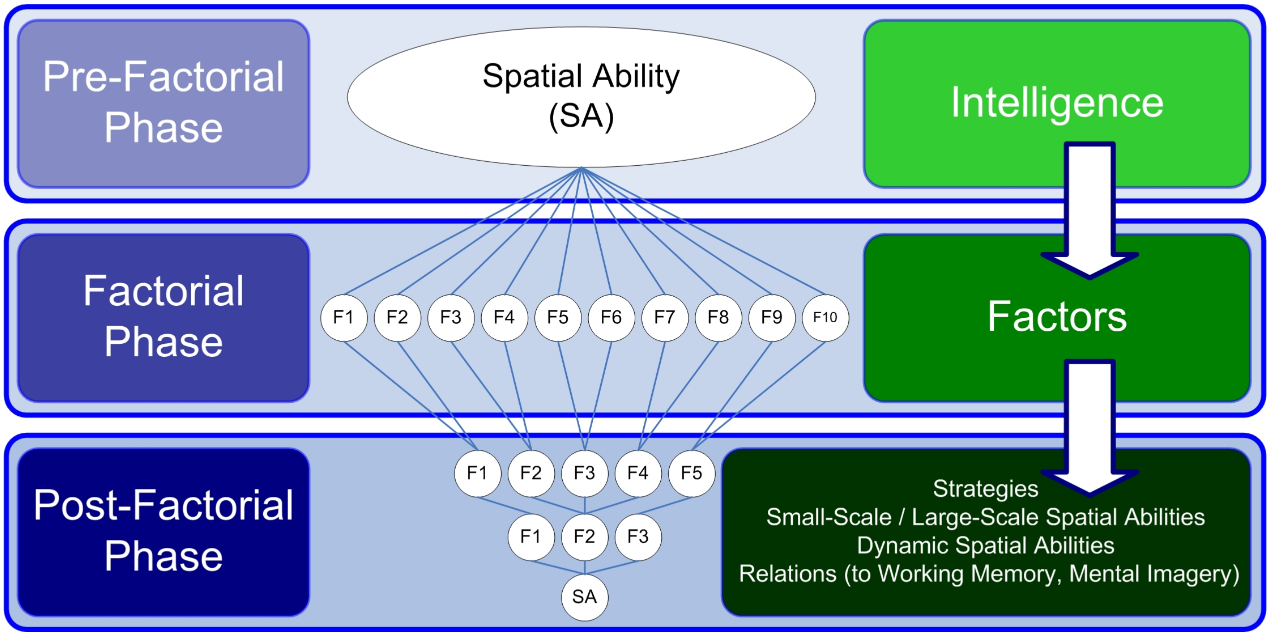

Figure 2: The three phases of spatial ability development and their programmatic key aspects

3.1. Visualization

For tests in this area objects are frequently divided into several parts and rotated (Fig. 3). The picture on the left shows four congruent equilateral right-angled triangles. The task is to find out which of the figures on the right can be built from the four triangles on the left?

Three-dimensional questions on this component frequently show a body in perspective view (e.g., cube or pyramid) which is to be cut in such a way that two predetermined bodies are generated.

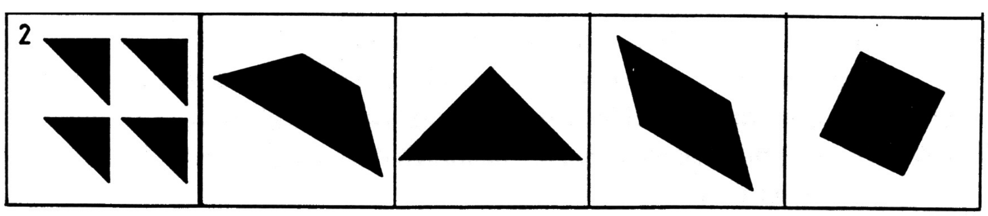

Figure 3: A typical question on visualization [30]

Guilford defines the factor as *an ability to think of changes in objects, changes in position, orientation, or in internal relationship* [13].

In many models of spatial ability the factor visualization is delineated as THE general factor, as it is the most comprehensive one [28]. Often the factors spatial perception and spatial relation are not viewed as independent and are both attributed to the factor visualization.

3.2. Spatial perception

Spatial perception comprises the ability to identify the horizontal and vertical, whereby orientation to one's own body plays an important role [26]. Regarding this component the following is a typical task, showing a cube half-filled with water: Which of the four cubes a, b, c, and d displays the water surface correctly?

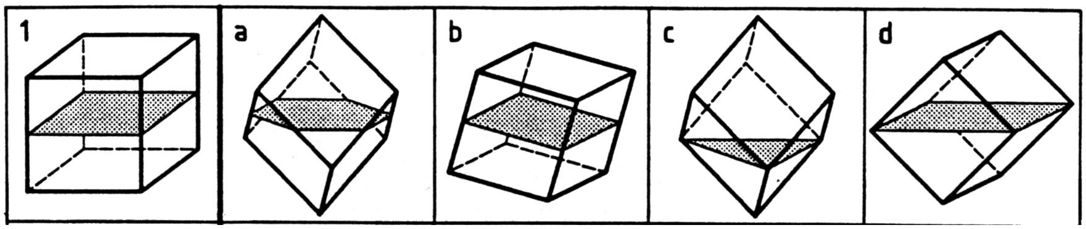

Figure 4: A common question on spatial perception [30]

3.3. Spatial relations

This component of spatial ability focuses on putting two- and three-dimensional objects in place. The following figure shows a common task: into which of the four cubes does the object on the left fit?

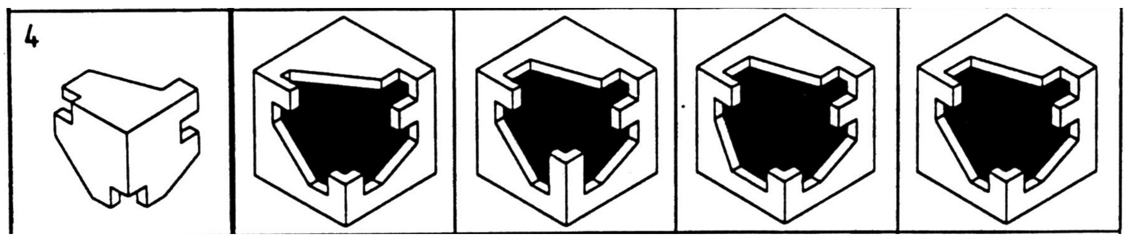

Figure 5: A common task on spatial relations [30]

The spatial relations factor cannot be seen as completely independent from the visualization factor [33]. They are similar because they both rely on executive functioning and visuospatial storage.

3.4. Mental rotation

The component comprises the ability to imagine the rotation of two- and three-dimensional objects. Geometrical objects have to be identified, often in varying positions and have to be rotated mentally. Two-dimensional tasks display geometrical figures (e.g., the letter z or the number 2) in varying positions (either rotated or rotated and mirrored).

Tasks on mental rotation often do not only test the correct solution of the task but also the speed with which simple figures can be rotated mentally by the probands. In most cases the decision is whether two rotated figures are identical or not. The process of mental rotation can be divided in four discrete stages of processing [5]. At the first stage individuals are encoding the stimuli and storing the information in working memory. The process of the second phase is rotating the mental representations. This stage of rotation is suggested to be a composite of several processes. Different parts of an object are often rotated separately. The third phase of processing involves comparison of the stimulus representations to decide whether they are identical or not identical. Finally, during the fourth phase individuals are responding positively or negatively depending on the outcome of the comparison. The amount of the time used for encoding, comparing and responding is nearly the same regardless of the angular disparity between the two shapes. Cooper & Shepard [5] stated that only the second stage of processing (rotation of the mental representations) is affected by the orientation of the shape. Individuals who are unable to achieve a stable holistic internal representation of a shape have to rotate the object several times. *High-ability individuals may* *be able to create more accurate internal representations* [37] of familiar und even unfamiliar shapes and can keep in mind the complete mental representation during the whole spatial rotation process. They are even able to encode and compare stimuli faster [37]. In many test samples the data recorded show a linear correlation between the angle of rotation and the time needed for the solution. At the beginning of this research tradition it was deduced from the test results *that mental rotation can be regarded as "analog", which means that manipulation of the picture before the "inner eye" follows similar principles as real manipulation. This assumption has meanwhile been disproved in various aspects, as mental rotation is successful only with comparatively simple objects* ([11]; citation translated).

The following Fig. 6 shows a typical task on mental rotation, published as the 'Mental Rotation Test' by Vandenberg, based on analyses by Metzler and Shepard [38]. Which of the four figures on the right are identical with the one on the left, composed of ten small cubes?

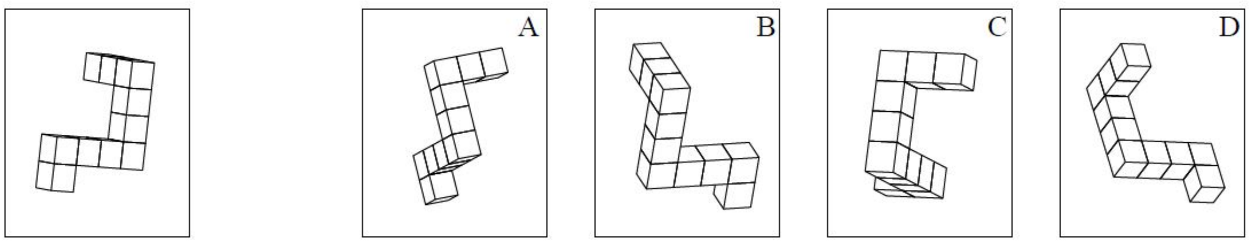

Figure 6: A common task on mental rotation [38]

3.5. Spatial orientation

This feature outlines the ability to find one's way in a three-dimensional space mentally as well as in reality, whereby one has to move around a spatial arrangement of objects. Typical tasks for probands are to put pictures taken during a boat ride into the right order [12] or to do the same with a sequence of pictures taken from a helicopter. Often the probands move in virtual, interactive surroundings to solve the tasks.

The acquisition of skills in spatial orientation can be identified in three hierarchical steps:

1. Orientation to landmarks: Orientation to points of reference in the landscape, e.g., high-rise building, power pole, lighthouse etc..
2. Studying routes: Linking landmarks with paths and routes.
3. Making map-like pictures: All the objects become interrelated, so that relative positions, shortcuts, distances etc. can be deduced.

Spatial orientation is the one of the spatial ability factors with the expectation that the individual moves mentally (move self) and is changing his/her mental perspective. Researchers have shown that when individuals change their egocentric perspective mentally, this leads to an activation of the left parietal-temporal-occipital junction, whereas when transformations are object-based (move object) and not individual-based, it leads to an activation of posterior areas mostly in the right hemisphere [48]. So we can suggest that the factors visualization (move-object strategy) and spatial orientation (move-self strategy) are indeed different spatial abilities. Kozhevnikov & Hegarty [24] after a study with the perspective-taking test stated that apparently object manipulation ability and perspective changing ability do not reflect the same construct.

They also found out that individuals use move-self strategy when they have to change their perspective with an angle of 90 degrees or more. If they have to rotate their position less than 90 degrees, they use move object strategy [24]. This is the reason why the Guilford-Zimmerman test is not an acceptable marker for spatial orientation because there are only tasks with differences in the angle of only about 30 degrees and individuals mostly use move-object strategies to solve these tasks [2].

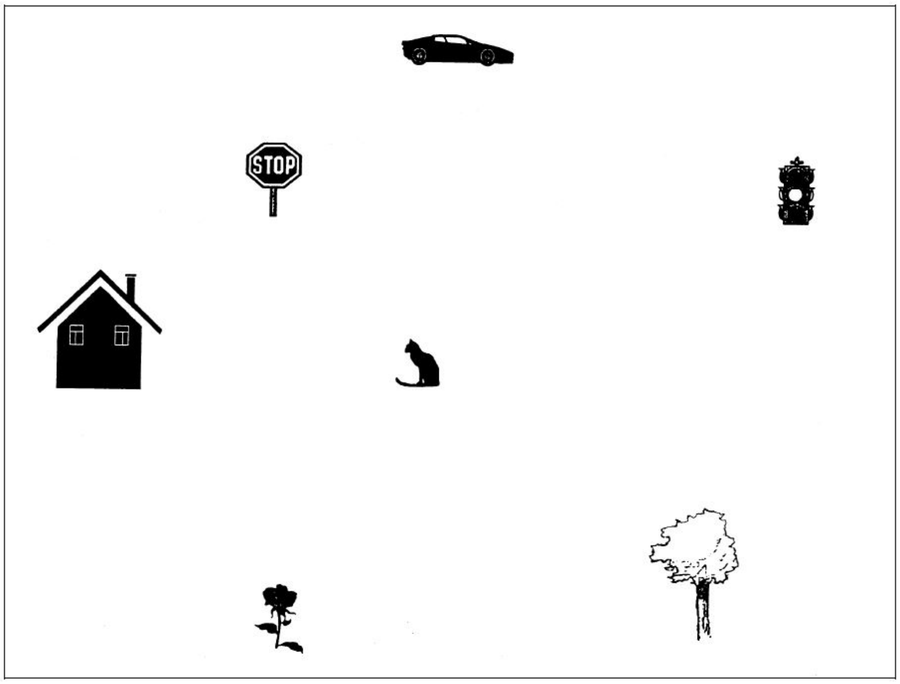

Figure 7: A common task on spatial orientation [17]

4. Discussions and perspectives

4.1. Small-scale and large-scale tasks

The traditional spatial ability research is mainly dealing with spatial ability tasks which can be solved with paper-and-pencil tests. These "classical" tests include tasks such as paper folding, rotation of shapes, solving mazes and finding hidden figures and they are all set in a small scale space or figural space [34, 35]. Montello [34] divides space into three categories: figural, vista and environmental space. Figural space can be overlooked from a single viewpoint, is external to the individual and is small in scale. Vista space is as large or even larger than the body and can be overlooked by one individual from a single place without movement (e.g., rooms or town squares). Environmental space is much larger than the body and can only be apprehended with locomotion (e.g., big buildings, districts of cities or even cities) [34].

Another classification of space was described by Previc [39]. He divided space into four realms. The peripersonal space (which is near one's body), second the focal extrapersonal space (which is the space of visual search and object recognition), third the action personal space (which is topographically defined), and fourth the ambient extrapersonal space (which includes bigger cities, areas and regions).

But do we really use different spatial abilities when we operate in different scales? Neuroscience research provides numerous arguments that we use different brain structures and mechanisms when we operate in different scales of space. Small-scale tasks (e.g., mental rotation) activate the parietal lobes [22], and when we operate in large-scale space the medial temporal lobe is activated [36]. Previc [39] also provides evidence that we activate different brain-areas when we deal with different space scales: For peripersonal space tasks we activate the dorsolateral area, for focal extrapersonal space tasks we need the ventrolateral area, for action personal space tasks we activate the ventromedial area and finally, for ambient extrapersonal space tasks the dorsomedial area [39].

Does that mean that small-scale abilities and large-scale abilities are not related because they have been processed in different areas of the brain? Hegarty et al. [19] proposes a partial dissociation model where three areas are represented (Fig. 8). The overlapping area shows the common abilities for small-scale and large-scale spatial learning. There is no evidence if there are any processes which are specific for small-scale spatial tasks. The research of Hegarty et al. [19] provides the fact that in addition to small-scale abilities there is the process of spatial updating (also called "self-report sense-of-direction") for large-scale spatial layout learning. Self-report sense-of-direction is the ability to update one' s position in space when moving self and is largely independent of small-scale spatial abilities.

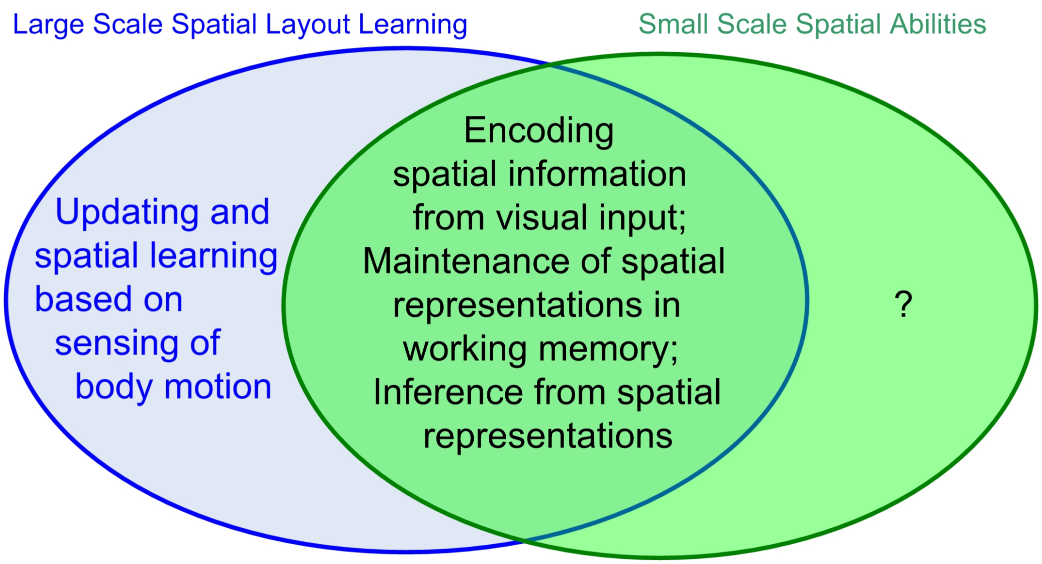

Figure 8: Model of the relation between Large Scale Spatial Layout Learning and Small Scale Spatial Abilities [19]

4.2. Dynamic spatial abilities

Traditional spatial tests are paper-and-pencil tests in which probands have to mentally manipulate mostly small objects and solve problems like card rotating or paper folding. Several researchers (e.g., [20, 8]) stated that we also should put a focus on dynamic spatial abilities, in which reasoning about moving stimuli is required. It is the ability to reason about moving objects, the ability to integrate spatial information over time and to judge absolute and relative velocities as opposed to static spatial abilities. Research in this field is actually in its infancy. We can notice controversial statements. Hunt et al. [20] after different static and dynamic tests and factor analyses conclude that the ability to reason about dynamic spatial relations is a distinct factor of spatial abilities. Larson [25] was testing with several dynamic and static rotation tasks and, after analyzing the results, stated that more evidence is required to see whether static and dynamic spatial abilities were differing.

4.3. Working memory and mental imagery

Hegarty & Waller [18] defined working memory *as the system specialized for maintenance of information in an activated state, necessary for task performance, and for executive control of attentional resources in order to maintain task goals, inhibit distracting information, and schedule different subprocesses required to accomplish a complex task* [1, 7, 33]. These researchers divided working memory into two different parts: First "short-term-memory" for tasks in which nearly no maintenance of information is required (e.g., digit span) and second "working memory" for tasks where maintenance of information is required. Hegarty & Waller [18], after several studies, came to the conclusion that there is no clear distinction between short-term-memory and spatial working memory, but a close link between individual differences in spatial working memory and spatial abilities can be observed. They also brought up the question why the spatial ability factors spatial visualization and spatial relations do not seem to be completely independent of each other. They are connected insofar as they both rely on executive control and spatial storage.

Differences regarding the working memory can be observed by studying low- and high-spatial individuals. High-ability individuals are supposed to have a better quality of the spatial representations that they mentally construct and they are better able to maintain this quality during and after transforming the stimuli, whereas low-ability individuals lose information while mentally manipulating objects [18].

There have been only few studies dealing with the relation between individual differences in mental imagery and mental abilities, maybe because the traditional studies for mental imagery use experimental methods. Mental imagery is the ability to maintain and transform vivid mental images. By summarizing the results of studies regarding mental imagery and spatial ability we can note the following aspects: Kozhevnikov et al. [23] identified two types of "visualizers" *("visualizers" are those individuals who rely primarily on imagery when attempting to perform cognitive tasks, "verbalizers" prefer to process information by verbal–logical means)* on the one hand those with high spatial abilities and on the other hand those with low spatial abilities. Low-spatial "visualizers" are good at visual imagery tasks such as interpreting degraded pictures and poor at spatial imagery tasks such as mental rotation, and high-spatial "visualizers" are processing the other way round [23]. So vividness of mental imagery seems to be unrelated to spatial ability whereas the ability of transforming images accurately is related to spatial ability. We can also assume that the ability to construct vivid mental images is different from the ability to manipulate and detect patterns in images [18].

4.4. Strategies

In the Post-Factorial Phase of spatial ability research (since 1994) scientists have begun to realize that studies on the spatial ability factors render no clear-cut or definitive results. Many researchers believe that one main reason for this dissatisfying situation could be the fact that probands use varying strategies in solving given tasks. Therefore the focus was shifted to the identification and analysis of diverse strategies used for solving spatial tasks.

Some typical statements are the following:

- *As the probands use differing strategies in solving tasks we find pronounced correlations and dependencies between all components of spatial ability. In some cases the intended solving strategies are practically not even used at all* ([29, p. 69]; citation translated).
- *Common alternative solving strategies using other cognitive abilities or different spatial and visual references should thus find recognition* ([29, p. 55]; citation translated).
- *Therefore it appears more recommendable to view the solution strategies for spatial ability tests when giving a general definition of spatial abilities* ([41]; citation translated).
- *[...] especially the strategies used are most interesting* ([16]; citation translated).
- *The flexible use of strategies or the adequate use of a strategy depending on the given task is a key factor for the optimal solution of spatial tests* ([11]; citation translated).
- *The amount of strategies and the flexibility in adapting them to the respective task is more relevant for achievement than simple basic cognitive processes* ([15]; citation translated).
- *One of the major problems is that tests are solved in different ways by different subjects. Subjects change their solution strategies with practice or when items' difficulty increases* ([27, p. 174]; citation translated).

Current key aspects in research are the identification and evaluation of varying strategies used by probands in solving spatial tasks. The identification of possible crosslinks between the factors of spatial ability and the strategies in solving tasks could be an additional interesting and in-depth analysis. First trends in this direction can be observed in the Post-Factorial Phase. A further paper will discuss the strategies which have been identified so far and how the knowledge of varying strategies have influenced the didactics of teaching geometry.

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