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SPATIAL ABILITY: UNDERSTANDING THE PAST, LOOKING INTO THE FUTURE

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Abstract

Spatial ability (SA) refers to the ability to generate, retain and manipulate abstract visual images. From 1880 to 1940 SA was gradually understood and defined as an independent, unique ability and justly included as one of Gardner's types of intelligences. Later, Maier improved Gardner's model by distinguishing between five types of spatial abilities and intelligence: Spatial perception, Visualization, Mental rotation, Spatial relations and Spatial orientation. During the 70's and 80's the developmental attributes of the term were addressed. Those studies wished to understand how and when SA develops and naturally were directed mostly at children as subjects. Those studies revealed that SA is an essential ability to the development of mathematical skills. Later developmental studies addressed adult SA development and accordingly found that SA was a predictor of success in STEM fields of academic studies. Furthermore, during those years psychometric studies started to develop standardized tests to measure SA. Starting from the 80's and up to now, a great deal of research is being directed at technology and the way it influences SA development. These studies direct special attention at studying how new technologies such as computer games and VR affect SA measuring and training. The current research wishes to continue the rich tradition of this field of studies and draws attention to first year engineering and architecture students. It seeks to investigate how to best train their SA and the way this training will influence future achievements on both fields.

Keywords: Mental rotation, spatial ability, spatial perception, spatial visualization, spatial relation

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1. What is Spatial Ability?

A great body of research throughout the history of science addressed questions about human abilities, how they are developed and how these abilities contribute to performance in different fields. Gardner's theory of multiple intelligences defines seven different types: linguistic, logical-mathematical, spatial, musical, physical-kinaesthetic, interpersonal and intrapersonal. The spatial intelligence is defined by Gardner (1983) as the ability of forming a mental model of the spatial world and maneuvering and working with this model. Spatial intelligence helps the individual to perceive, decode and activate in the imagination visual representations that create the image of space. Researchers in this field consider SA an ability consisting of a set of cognitive skills and list its components. According to Gardner (2011), spatial intelligence includes several capabilities:

1. The ability to accurately capture two-dimensional shapes or objects in space.
2. The ability to imagine and graphically represent visual or spatial ideas.
3. The ability to evaluate what a shape or object will look like after imagination's manipulation.

Armstrong (2018) states that spatial intelligence consists of three components:

1. The ability to absorb and understand visual information: The ability to distinguish similarities and differences between objects or between object's parts; The ability to understand shape globally; The ability to identify relationships between visual factors and the ability to distinguish between character and background; The ability to absorb and understand visual information makes it possible to translate the visual information into the properties of the object to which the observed information relates.
2. The ability to create a mental image: The ability to imagine objects from their two-dimensional representations or from verbal information.
3. The ability to perform manipulations by imagination on a mental image. For example, the ability to imagine movement of objects or imagine changes and processes in them. In this activity also the source and the product of mental processing are also visual, and the emphasis is on the mental process that the individual goes through while simulating a change that has happen in object.

According to Armstrong (2015), people with spatial intelligence think and learn with the help of pictures; remember faces and places; Notice small details that most people do not notice; Connecting between the world of reality and the world of imagination that they envision. They think in three dimensions, imagining three-dimensional things in their head and "looking" at them from different angles.

Most studies use the term Spatial ability (SA) and it is generally attributed to spatial perception or visualization (Grande, 1990). In this study we will use the following definition: SA is the ability to generate, retain and manipulate abstract visual images (Lohman et al., 1979).

The research on SA started at the end of the 19st century. Those studies focused on acknowledging and defining SA as a unique and separate ability, this as part of a general movement away from understanding intelligence as a holistic construct and towards perceiving it as combined of diverse set of skills such as associative memory, numerical ability, verbal fluency and understanding etc. (Thorndike, 1921).

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2. Psychometric Perspective

From the fourth and the fifth decade of the 20st century psychometric studies began. Those studies were directed at defining and measuring the different elements of SA. For instance, Thurstone (1950) found three elements of SA which eventually became known as: mental rotation, spatial imagery & spatial perception (Linn & Petersen, 1985). Naturally at that time, there was no unity regarding the test and methods of measurement and sometimes, those differences even led to contradictory definitions of the SA elements (Tzabary & Tesler, 2022). The psychometric branch of studies continues to these days and keeps refining the distinction between the different subtypes of SA and the best way to measure them. After Gardner’s work, SA was more accurately laid out by Maier (1996) who improved Gardner's multiple intelligences model and theory when distinguished between five types of spatial abilities and intelligence:

1. *Spatial perception*: The horizontal and the vertical fixation of the direction regardless of disturbing information.
2. *Visualization*: This is the ability to describe situations when the components pleasant to each other.
3. *Mental rotation*: rotation of three-dimensional solids mentally.
4. *Spatial relations*: The ability to identify the relations between the parts of solid.
5. *Spatial orientation*: The ability to enter a given spatial state.

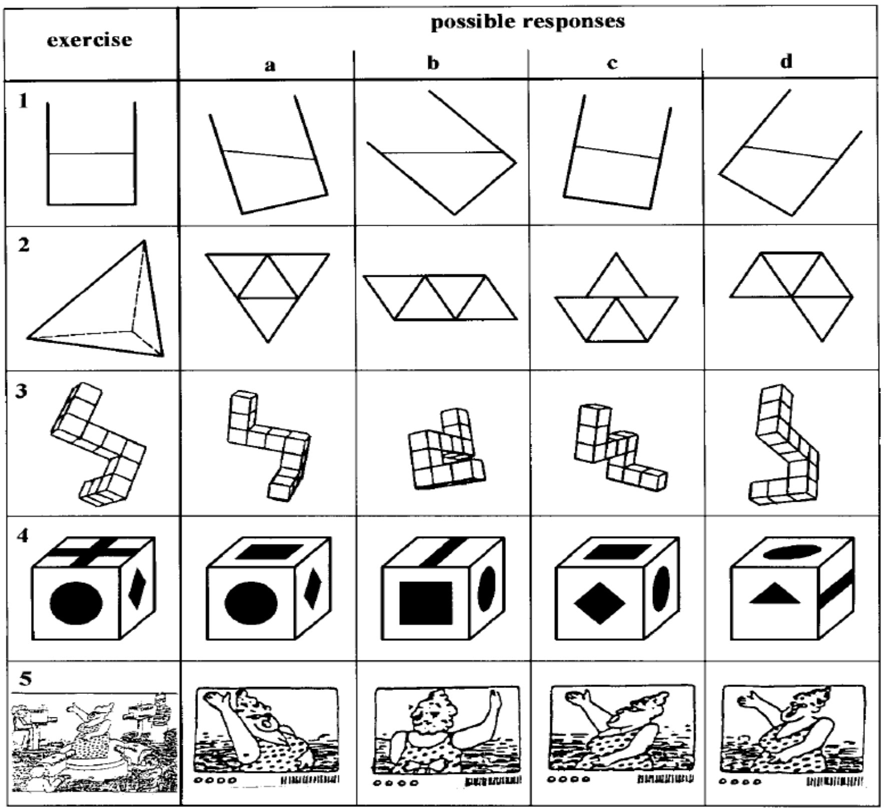

Figure 1. Exercises of the five elements of SA, Maier (1998)

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Recent studies suggested other perspectives on how to view SA such as the distinction between static SA and dynamic SA (D'Oliveira, 2004) or the distinction between intrinsic SA and extrinsic SA (Newcombe & Shipley, 2015).

3. Developmental Perspective

From 1960-1980 the development of SA was addressed in a more serious manner. These studies wished to find out when SA develops and how. Thus, Piaget and Inhendler showed SA to be an essential ability from birth and specified three stages of development: 1. Typological stage- usually children from the age of 3-5 acquire two-dimensional abilities that are tied to qualitative relations between shapes such as closeness, separation, order etc. and also the distinction between open and closed shapes. Children who successfully reach this stage are capable of completing a puzzle but they draw a square, a triangle and a circle the same way (round closed line). Children at these ages are still egocentric and are unable to understand that there may be more than one perspective. 2. The Projective stage- at this stage children learn to distinct between a straight and curved line and between different polygons. They learn to imagine different three-dimensional objects and understand how they look from a different perspective or after rotation. This stage is usually acquired at the age of 6 and keeps developing throughout all the years of childhood and adolescence. 3. The Euclidean stage- at this stage a transition is reached from two-dimensional to three-dimensional reasoning, thus the ability to form and use terms like direction, angle, relation volume etc. is possible (Beard et al., 1971). Current studies indicate that Piaget's stages are correct but that the age at which they are reached is younger (Huttenlocher et al., 1999). Verdine et al. (2017) developed a test that measures SA ability in children as young as three years old. In their Longitudinal study they found that SA ability at the age of three predicts SA ability at the age of five.

Can SA develop at adulthood?

Hoffer (1977) describes a research conducted on people who were blind from birth (because of cataract). These people could identify objects by other senses such as touch, taste, smell and hearing. Because of developments in the medical world they have gone through surgery and as a result could see for the first time. After surgery the subjects were presented with objects that they could only see and could not identify them. For those people shapes like pyramids or cubes had no visual meaning. But with time, they were able to develop this understanding and learned to know and interpret the visual information and to combine it with knowledge from other senses. Hoffer saw these results a proof that visual perception can develop at adulthood . furthermore Special courses given to students whose mastery of spatial skills was low contributed to a marked improvement in their achievement. These findings also indicate the ability to develop SA.

4. SA and Other Abilities

After the developmental research was grounded, researchers began focusing on the relationship between SA and children's mathematical achievements and capabilities. These studies have shown that SA plays a major role in mathematical thinking (Mix et al., 2016; Wheatley, 1990). One of the common theories about the way this effect occurs, explains that mathematical thinking is supported by spatial-

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mental representations (Cheng & Mix, 2013), Thus, for example, some people create schematic representations of mathematical problems that include the spatial relationships described in the problems. Studies indicate that the solutions offered by these people are more correct on average (Rittle-Johnson et al., 2019).

Later studies have shown similar correlations between SA and mathematical thinking in college students (Wai et al., 2009). According to these studies SA is among the cognitive factors that were identified as predictors of success in STEM fields (Science, Technology, Engineering and Math) (Richardson et al., 2018; Wainman et al., 2021). Large scale studies show that SA can predict long term achievements in STEM, better than verbal and quantitative abilities (Wai et al., 2009).

Recent studies have turned the focus on another relevant field in which SA plays a vital role, the field of architecture (Berkowitz et al., 2021). Architects need good mathematical competences. For example, they need to be able to find the strength of a certain structure or identify the optimal way of stabilizing a structure, and so on (Sergeeva et al., 2019). Furthermore, when architects design a building, they perform a multi-step process of manipulating spatial configurations, switching between perspective and so on (Cross, 2011). Thus, the ability to visualize space is an integral skill in architecture (Berkowitz et al., 2021). Having said that, it seems that the way SA influences on success in architecture studies was not studied yet.

5. SA Training

Experts agree that it is important to develop a child’s spatial abilities from a very early age (Tzabary & Tesler, 2022). Thus, it was found that playing puzzle games at the age of 2-4 can predict spatial abilities, even when variables such as parent’s educational degree, income etc. are being controlled (Levine et al., 2012). It has also been found that goal-directed construction play with parental support contributes to the development of SA rather than open play in which the child builds as he sees fit. In such a game the child is required to solve a certain problem in order to reach the goal, and for this purpose he is expected to use more spatial intelligence (Ferrara et al., 2011). Newcombe et al. (2013) also states that the use of symbolic representations such as maps, models, graphs and spatial hand gestures has an enormous effect on the development of SA in child’s early years of life. The use of spatial representations allows to pass spatial knowledge and encourages spatial communication between parents and children that includes the use of words to describe spatial relations such as: above, behind, under etc. this communication influences how well children from the age of 1-4 understand and use spatial language and in turn predicts their spatial abilities (Pruden et al., 2011). Also, studies have shown that the presence of an adult that talks, guides and encourages a child’s learning while pointing his attention towards the difference or resemblance between shapes, helps him to sort them into categories and motivates him to explore the world around him, will enhance development (Levine et al., 2016).

Further, it was found that gestures have a big role as means to aid SA skills. A gesture can represent and object, point to a specific direction, it can also describe spatial relations etc. usually gestures accompany speech and add extra information (Newcombe et al., 2013). Thus, it was found that gestures improve college student’s achievements in mental rotation tasks (Chu & Kita, 2011). Students who were encouraged to use gestures without speech did better than those who weren’t given any instructions or

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those who were banned from using gestures. In accord with these findings teachers should use gestures in their teaching to better develop student's SA (Newcombe & Frick, 2010).

Real, tangible teaching vs computer-based learning:

Maier, who introduced the five different types of SA (presented above), wrote that based on psychological research findings, all five elements of SA have to be specifically trained. He further introduced a modular construction system based on the traditional system where polygons were joined with rubber bands. He used real models, because in his view those were the most successful in improving students SA (Maier, 1996). Current studies support Maier's approach, they state the use of real models is more effective in developing SA that computer based learning (Hill et al., 2010). Sorby (1999) reports on a study conducted among engineering students and examined what develops their spatial imagery ability. It was found that in courses where students were required to draw models by hand (rather than using a computer) and work with tangible models (rather than models on a computer monitor), there was a development in their spatial performance. Although effective, this intervention is costly since it requires an expert teacher, it is also long and needs a lot of models if the students work individually (Aszalos & Bako, 2004).

Later there has been a computer-based training program, developed by Aszalos and Bako. This intervention seeks to improve student's spatial geometry ability and according to the results did so with success. Nevertheless, this intervention was preliminary and limited in the kind of ability tested to improve geometry and in the number of subjects. Yang and chan, 2010 found that digital pentomino games (cutting and assembling riddles of forms that are comprised of 5 squeres) can improve spatial skills.

Baldwin (2003) and Orion et al. (1997) report a development in spatial performance following an intervention program as part of a course in earth sciences. The studies were conducted among different populations: middle school students, geology students and non-science students, and all study groups have developed certain improvement.

From 1980 and to these days many studies focus on the influence of technology on SA and it's measurement (Mohler, 2001). The great technological revolution that became evident in the fields of computers, medical equipment, VR etc. led to new possibilities in the research of SA. Accordingly, researchers started looking into training programs that can improve children's and adult's SA.

Thus, computer based training programs are gaining more and popularity these days (Kurtulus & Uygan, 2010). Rafi et al. (2008) examined the effect of Web-based activities and animation aided computer applications on the spatial visualization

abilities of two test groups of primary school 2nd Grade students. The control group in this study was taught through traditional teaching methods. Results indicated that the two test groups had higher levels of spatial ability than that of the control group (Rafi et al., 2008).

Another technology that was implemented for the purpose of developing spatial skills is 3D dynamic sketching software that enables a more learning experience.

Kurtulus and Uygan (2010) developed a training program aimed at improving spatial visualization. In order to improve this ability, they used a 3D dynamic sketching software that is usually used for designing 3D building models. This study found significant differences in students' visualization abilities

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in a pre-post intervention design between test (sketchup training) and control group (traditional geometry activities) (Kurtulus & Uygan, 2010). Recently Jaelani (2021) compared students who were receiving SketchUp-aided generative learning and direct learning in high school students. The results showed that spatial ability increased after receiving SketchUp-Aided generative learning compared to direct traditional learning (Jaelani, 2021).

Most recently, Di and zheng conducted a meta-analysis of virtual technologies training programs for improving SA. This study encompassed 36 empirical studies published between 2010 and 2020. They found that virtual technologies were effective in improving student's SA, this effect was especially high for preschool learners, in the fields of natural science and engineering technologies, for all types of spatial ability, and when learning during 3 to 6 months. Furthermore, augmented reality was most conducive to improving learners' spatial ability compared with other virtual technologies (Di & Zheng, 2022).

6. Summary and Discussion:

As laid out in this article, spatial ability is a term long defined and studied. And indeed, it came a long way until reaching its current definition, psychometry and the theories behind its development. Though research keeps being done in all these arias, and some disputes are still evident and fuel future studies, it seems to me that the one unsettled area of spatial ability research remains the area of training and improving SA. In this field it seems that despite many studies conducted, there is no movement towards a more accepted, unified, standardized approach to train SA. On the one hand, there is Maier's approach, which states that all five subtypes of SA should be trained, using traditional real models, since in his view those were the most successful in improving students SA. Current research supports Maier's approach by pointing to the advantages of training programs and college courses that encourage tangible learning through working with models, using gestueres, drawing etc. On the other hand, there are multiple studies that presented the training of one specific type of SA such as mental rotation or visualization, using computerized methods only (Aszalos & Bako, 2004). Some studies trained SA through requiring students to draw models by hand (Sorby, 1999), others stated that VR and 3D training is better (Rafi et al., 2008). Also, almost no research was found to address the question of combining tangible and computer based learning. It seems to me that there is no consensus in this regard and there is a lack of a more unified approach, combining the different methods and creating a general guideline to training SA. Such an approach is extremely important considering the great evidence found for the importance of SA in cognitive development and later achievements. Finally, the vast majority of studies regarding SA were conducted on one specific population, this is the population of STEM fields (both in children and in adults) and little attention was given to other fields such as architecture (Berkowitz et al., 2021).

In my study I seek to deal with the problem laid out above and to try and develop a multidisciplinary training program, directed at improving SA in both engineering and architecture students. A program that will combine both frontal learning, using real life models and by hand drawing, and computer-based learning, using sketch-up and VR technologies. I wish to create a balance between different forms of learning, addressing the different needs and deficits of the educational systems (shortage in expert teachers, need for cost-effective, short term interventions, on-line learning etc.). In this way I wish to optimize the process of learning, to better engage and motivate students and to create a cost-effective training program that will serve as the basis of a unified method of training SA.

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