

# Developing a Spatial Ability Framework to Support Spatial Ability Research in Engineering Education

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**Abstract:** *The association between high levels of spatial cognition and success in a number of engineering and technological fields is widely acknowledged within the pertinent literature. There is now a need for further investigation to explicitly identify the causation underpinning this correlation. An extensive literature review was carried out with the objective of systematically defining spatial ability and identifying its constituting spatial factors. The literature review uncovered a number of critical considerations which merit recognition for spatial ability research. The significance of this paper lies in the presentation of these considerations as underpinning criteria for a new comprehensive theoretical framework which would ultimately map out the cognitive domain of spatial ability. It is anticipated that such a framework could be used to guide future research that investigates the significance of spatial ability within engineering education.*

## Context

The correlation between high levels of spatial ability and success in a number of engineering domains including engineering education is extensively acknowledged within the relevant literature (Hamlin, Boersma, & Sorby, 2006; Harle & Towns, 2010; Larson, 1996; Lubinski, 2010; Maeda & Yoon, 2012; Maier, 1994; Norman, 1994; Schneider & McGrew, 2012; Sorby, 1999, 2009; Wai, Lubinski, & Benbow, 2009). There is now a need to explicitly identify the causation underpinning this relationship. A potential factor of causation may be that “*most engineering education students are visual, sensing, inductive and active*” (Felder & Silverman, 1988, p.680) and that having a high level of spatial ability affords such students the capacity to better interact with and manipulate relative visual stimuli. A holistic view of spatial ability is often attributed to success in this field, however it has been posited that individual spatial factors are relevant to success in specific engineering educational tasks. For example, the Imagery (IM) factor which refers to the capacity to mentally produce vivid images has been suggested as an important cognitive factor for solving geometric problems (Schneider & McGrew, 2012). These spatial factors are what ultimately constitute a person’s level of spatial ability and spatial skills. Unfortunately within the pertinent literature the identification and classification of spatial factors is a contentious issue from which many misconceptions have evolved. Therefore, the objective of this paper was to carry out a systematic literature review exploring spatial ability and spatial factors to instigate the development of a comprehensive theoretical spatial ability framework. This paper presents the initial stages in the conception of a new framework and defines the core elements which will ultimately serve as its underpinning structure. The significance of a spatial ability framework for engineering education lies in acknowledging the visual and dynamic environment of engineering. Additionally, in such an environment where high spatial

capacities correlate highly with success it is imperative that a common conception and language exists to guide specific research into defining core spatial competencies.

## Defining Spatial Ability

Since its conception as a primary cognitive ability, the definition of spatial ability has been a contentious issue. For example, in Thurstones (1938) model of primary mental abilities it was classified as 'Space' while in the Spearman-Holzinger model which was embodied in Spearman's (1939) re-examination of this work it was known as 'Spatial Relations'. This characterization of a non-ubiquitous conception continued and remains in existence today. Surviving now is a multitude of definitions attempting to describe spatial ability as well as unique spatial factors. The tension between definitions for spatial ability offered within the literature now creates the need to formulate an explicit definition. This definition is essential to guide the literature review and support the identification of core elements of a theoretical framework. It is posited that one of the sources of the current contention within the spatial factor literature is the variety of definitions ascribed to the concept of spatial ability. The need is therefore created within the diverging discourse to subscribe to a universal understanding of this cognitive ability. Despite the range of descriptors for spatial ability there are dominant definitions offered. Lohman (1979) defines spatial ability as *"the ability to generate, retain, and manipulate abstract visual images"* (p.126) and Gaughran (2002) defines it as *"the ability to visualise, manipulate and interrelate real or imaginary configurations in space"*. Sorby (1999, p.21) however, defines spatial ability as the *"innate ability to visualize that a person has before any formal training has occurred"* and differentiates it from spatial skills which she defines as *"learned or are acquired through training"*. Finally, a recent project (Sutton & Allen, 2011) focussing on assessing and improving spatial ability in design based disciplines utilising online systems defined spatial ability as *"the performance on tasks that require: (a) the mental rotation of objects; (b) the ability to understand how objects appear in different positions; and (c) the ability to conceptualise how objects relate to each other in space"* (p.5).

There is legitimacy in all definitions; however there is a need to consider spatial ability as a holistic ability. Sorby's definition offers the additional characteristic that spatial ability can be an innate ability. This perspective was the basis behind the formulation of the concept of a spatial aptitude. Sorby (1999) also notes how prior to third level education the status of any spatial training is unknown which lends to the premise that spatial ability is best understood as a person's current level of spatial reasoning ability. Gaughran, Lohman and Sutton and Allen's definitions then offer more explicit insights concerning the cognitive functions involved in spatial reasoning. Taking cognizance of the aforementioned definitions, the following are now suggested:

- **Spatial factors:** Cognitive factors of intelligence in the domain of spatial ability. These are descriptive of a person's current cognitive stage and may be innate or specifically trained.
- **Spatial skills:** A person's capacity to appropriately utilise a spatial factor or multiple spatial factors to perform a task.
- **Spatial aptitude:** An innate level of ability which describes a person's holistic capacity within the domain of spatial ability, where no education or training specifically designed to develop spatial ability has taken place.
- **Spatial ability:** The current level of ability which describes a person's holistic capacity within the domain of spatial ability, after education or training specifically designed to develop spatial ability has taken place.

The discriminations provided by these definitions offers clarity to guide future research. The development of spatial ability should be a goal within engineering education and these definitions can assist in achieving this. With spatial factors being the core components of spatial ability, their development and elicitation are important to the engineering education

community. The link between spatial factors and spatial skills infers that by designing measurement instruments which require the adoption of strategies focused on spatial skills we can elicit empirical values representative of spatial factor capacities. The same link can also be incorporated into the design of interventions aiming to develop spatial ability. Taking further cognizance of the role of spatial factors on forming a person's level of spatial ability, the development of test instruments in this domain should cater for individual factors. This concept is similar in style to Ekstrom, French, Harman, and Derman's (1976) Kit of Factor Referenced Cognitive Tests where the approach is to measure each factor individually. Therefore, the development of a framework which can map out the individual spatial factors would make a significant contribution towards establishing general and targeted measurement instruments that could validly and reliably identify the characteristics spatial ability and spatial aptitude.

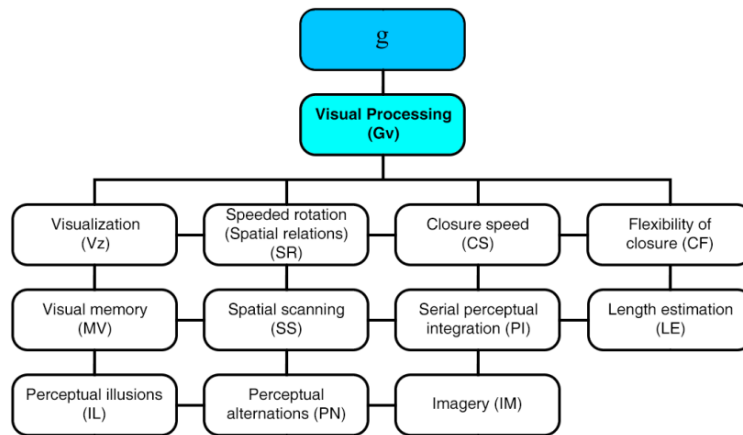
## **Uncovering the Core Elements of a Comprehensive Theoretical Spatial Ability Framework**

Since the early 1900's when the concept of spatial ability as a cognitive domain was first theorised there has been a substantial body of work carried out to uncover its constitutional elements. These elements are known as spatial factors and are typically elicited by factor analytic studies in the forms of both Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA). An extensive literature review was carried out to identify each unique spatial factor which has been established to allow for the instigation of the development of a new framework to illustrate this cognitive domain. The result of this analysis is the emergence of four distinct considerations which are imperative to the development of a comprehensive new framework. These are:

- There is ambiguity surrounding the existence of certain spatial factors resulting from their classification and therefore each factor must be analysed for uniqueness prior to its positioning on a framework.
- Many factors have been established within specific disciplines where prior knowledge may be a contributing factor. Prior semantic knowledge should not load a cognitive factor and therefore such factors should be analysed for validity.
- The literature presents a variety of similar spatial factors which have been identified across a variety of studies. Typically these have been posited through inference following factor analyses and should therefore be critically analysed for uniqueness.
- The dichotomy of static and dynamic spatial factors merits recognition.

This paper describes the relevance and influence of each of the above criteria in developing a comprehensive new framework.

Eliot and Smith (1983, p.1) note a phase in spatial ability research from 1938 - 1961 where research in this area attempted to "*ascertain the extent to which spatial factors differed from each other*". Typically, these studies measured spatial ability through paper and pencil tests where the stimuli are static. This has led to the development of multiple theoretical frameworks of intelligence which describe spatial ability as having a singular static dimension. For example, the Cattell-Horn-Carroll (CHC) theory (Schneider & McGrew, 2012) which is currently one of the most comprehensive frameworks available to use as a basis for work in many cognitive domains, describes the domain purely with static factors. The CHC theory was developed largely as a result of Carroll's (1993) extensive meta-analysis of cognitive factors and describes its containing spatial factors as belonging to the domain of Visual Processing (Gv). There are 11 unique spatial factors, each of which is well supported within the pertinent literature, described within this domain (Figure 1).



**Figure 1: Illustration of the domain of Visual Processing (Gv) within the CHC theory as described by Schneider and McGrew (2012).**

### **Ambiguity in Spatial Factor Classification**

While the CHC theory offers a broad view of the spatial ability domain it also further adds to continuing discussion regarding the existence of a Spatial Orientation (SO) factor. McGee (1979) summarises a variety of definitions found within the literature for this factor. Spatial Orientation (SO) is typically concerned with the perception of visual stimuli from multiple perspectives in space. The status of perspective taking factors and mental rotation factors has historically been an iterative topic. Despite many researchers identifying it as a core factor of spatial ability (Bodner & Guay, 1997; Linn & Petersen, 1985; McGee, 1979; Smith, 1964) it is currently not recognised in the CHC theory as an independent factor due to the difficulty in differentiating it from mental rotation factors. Hegarty and Waller (2004) posit that this may be due to a considerable shared variance between perspective taking and mental rotation factors as they rely on many common cognitive processes. Hegarty and Waller (2004), through confirmatory factor analysis, have shown evidence to support the dissociation of perspective taking factors from mental rotation factors. Their work is further supported by contemporary research (Wang, Cohen, & Carr, 2014) which discusses two forms of spatial ability: small-scale spatial ability and large-scale spatial ability. Small-scale spatial ability involves allocentric spatial transformation which requires a person to perceive the relationships between objects. Large scale spatial ability involves egocentric spatial transformation which requires a person to perceive the relationship between themselves and the object. This has been previously referred to as ‘Spatial Orientation’ (Kozhevnikov & Hegarty, 2001). The distinction between perspective taking and mental rotation factors provides merit for further exploration into a Spatial Orientation (SO) factor and as a result this factor deserves independent recognition. A recommended definition for this factor is the ability to manipulate your perspective in space to generate a holistic understanding of an object or of the larger environment.

Further ambiguity resides in the existence of a Spatial Relations factor. While currently not included as an individual factor in the CHC theory after being replaced by a Speeded Rotations (SR) factor, Spatial Relations does deserve additional research in order for a comprehensive decision to be made regarding its existence. Harle and Towns (2010) summarise the pertinent discussion regarding the classification of mental rotation factors concluding with Spatial Relations being considered as the primary mental rotations factor. However, this disagreement persists as evidenced through its non-existence in the current CHC theory. Tests such as the PSVT:R (Guay, 1977) which requires the rotation of complex geometries under relatively unsped conditions should be examined beside established tests of Visualization (Vz) such as the Foam Board Test or the Paper Folding Test and tests of Speeded Rotation (SR) such as the Card Rotations Test and the Cube Comparisons Test (Ekstrom et al., 1976) to generate further insight which may inform this discussion.

The Imagery (IM) factor is represented as a single factor in the CHC theory however, Burton and Fogarty (2003) carried out an extensive factor analytic study focusing on clarifying this factor. They qualified three unique imagery factors which they posited as Imagery Quality, Imagery Speed and Imagery Self-Report. The Imagery Quality and Imagery Speed factors reflect unique factors based on the definition of a spatial factor offered in this paper. The Imagery Self-Report factor does not conform to this criterion as it is a measure of a person's introspective perspective on their capacity to generate vivid images and is therefore not objective. This subjectivity means that the tests loading on this factor do not measure a cognitive skill but rather a perception of a skill.

Finally, a Perceptual Illusions (PI) factor is included as a single factor within the CHC theory however, Coren *et al.* (1972) suggests five individual factors based on factor-analytic results. Carroll (1993) made reference to this study and described it as a 'major factor-analytic study' (p.357), he later describes the potential for multiple illusionary factors based on this work. The findings suggest that individuals differ not only in the degree they are affected by visual illusions but also by which illusions affect them. The uniqueness of these five factors became apparent during the literature review. The five factors included are:

- **Shape and Direction Illusions:** The ability to not be affected by illusions of shape, parallelism and colinearity.
- **Size Contrast Illusions:** The ability to not be affected by illusions of contextual size.
- **Overestimation Illusions:** The ability to not be affected by illusions of overestimations of linear extent.
- **Underestimation Illusions:** The ability to not be affected by illusions of underestimations of linear extent.
- **Frame of Reference Illusions:** The ability to not be affected by frame of reference illusions.

### **Spatial Factors Influenced by Semantic Knowledge**

As spatial factors are the underpinning component of a person's spatial skills, spatial aptitude and spatial ability, a further understanding of the nature of these cognitive factors and how they interact during engineering educational tasks is of interest. Schneider and McGrew (2012) describe spatial factors as being "*Sensory- and Motor- Linked Abilities*" (p.128). These factors are concerned with the ability to manipulate visual stimuli and not to interrogate semantic knowledge. This understanding reinforces the stance that prior semantic knowledge shouldn't dictate a person's access to these cognitive resources. It is possible for a person to utilise a combination of semantic knowledge with spatial factors to solve a problem however, this semantic knowledge would be a separate factor contributing to that person's performance in that particular task. The CHC theory acknowledges this and describes a domain of factors qualified as '*Acquired Knowledge*' which appears underdeveloped but houses discipline specific knowledge factors such as a Mathematical Knowledge (KM) factor. Traditionally this has been a misconception within the literature with many researchers positing spatial factors which had this influential characteristic. It is therefore important to provide details on the spatial factors which contain this reliance within the literature to illustrate why they should not be considered as unique spatial factors.

Roff (1952) suggested two such factors which he named 'Plotting Ability' (PQ) and 'Directional Thinking'. Tests loading on these factors required participants to either understand coordinate systems or they could be influenced by prior directional knowledge such as of compass directions (Carroll, 1993). Neisser and Lorenz (1986) additionally reported three ecological spatial factors however; a participant's familiarity with the location appears to heavily influence these factors. Lee and Bednarz (2011) discuss a list of spatial thinking components which they integrated into their Spatial Thinking Ability Test (STAT). These are derivatives of the work of Golledge (2002) and Gersmehl (2005). There is a reliance on geographic knowledge encapsulated within many of these which means that not all of them can be accurately defined as spatial factors. These classifications may have

been beneficial to describe the results of spatial factors so as to assist in distinguishing the aspects which loaded on the tests.

### **Similarities in Uniquely Assumed Spatial Factors**

Within the pertinent literature there is evidence of similarities in the definitions being ascribed to uniquely assumed spatial factors. For example, some of the factors posited by Lee and Bednarz (2011) were actually previously well supported within the literature (Schneider & McGrew, 2012). They describe a factor concerning the capacity to comprehend orientation and direction which is an ability that forms the core of many discussions on spatial ability. Many other factors proposed within the literature are representative of already well supported factors. Johansson (1965), for example, identified a factor in age 7 children which she called 'Nonverbal Intelligence' however it holds a strong similarity with the Visualization (Vz) and Speeded Rotation (SR) factors. Gaughran (2002) discusses five spatial factors; four of these are either encompassed within pre-existing well supported factors or are descriptive of a whole factor. His fifth factor, Dynamic Imagery (SF5), described as the ability to manipulate individual elements of a component including the ability to explode and reassemble these components both requires substantial knowledge of the artefact and in addition involves the abilities outlined in the Visualization (Vz) factor. While not qualifying as independent spatial factors, Gaughran's framework does however appeal to engineering education as it offers a framework for the development of some elements of spatial ability for students.

Another set of factors which appear within the literature that do not qualify as spatial factors are those described by Saunders (1959). He initially described a Picture Completion factor however with further research (Saunders, 1960), he divided this into three individual factors. The *Maintenance of Contact factor* was ruled out as it describes a period of fixation with a visual stimulus during a test. An *Effect of Uncertainty factor* that was excluded as it describes a feeling of uncertainty which could occur with any form of stimulus not just visual. Finally, a *Maintenance of Perspective factor* was excluded as it describes the ability to perceive visual imagery which is encompassed within the Visualization (Vz) factor.

### **The Static and Dynamic Spatial Factor Dichotomy**

The literature review identified another dimension to spatial ability which is concerned with moving or dynamic stimuli. There appears to be a variety of these dynamic spatial factors which have been uncovered by multiple factor analytic studies with moving visual stimuli.

Larson (1996) notes the poor correlation between the dynamic real world and the two dimensional static tests commonly adopted when trying to elicit spatial factors. The engineering education environment presents a multitude of dynamic visual stimuli. The spatial factors within the CHC theory have all been qualified as static factors however, for further investigation into the role of spatial ability within engineering education a dynamic domain within spatial ability needs to be considered. The capacity exists to explore many well supported static factors in a dynamic context. Spatial Scanning (SS), Serial Perceptual Integration (PI) and Perceptual Alternations (PN) all have the capacity to be analysed with dynamic stimuli and can be interpreted as dynamic factors, it would be of interest to qualify if this would lead to the establishment of new independent factors. Dynamic alternatives to these should therefore be considered for inclusion in a new framework.

Subsequent to Carroll's (1993) work and with modern technology now allowing for further investigation into dynamic spatial reasoning, further studies have been carried out which support the existence of independent dynamic spatial factors. The concept that dynamic factors could exist was first investigated by Hunt and Pellegrino (Hunt, Pellegrino, Frick, Farr, & Alderton, 1988; Pellegrino, Hunt, Abate, & Farr, 1987; Pellegrino & Hunt, 1989) and this work provided a basis for two factor-analytic studies (Contreras, Colom, Hernández, & Santacreu, 2003; D'Oliveria, 2004) which were carried out to determine if dynamic spatial reasoning was distinguishable from static spatial reasoning. Both studies employed exploratory and confirmatory factor analyses with multidisciplinary study cohorts. The results

for both studies support the distinction between static and dynamic spatial reasoning. Both studies propose independent dynamic factors which are distinct from static factors. Contreras et al. (2003) identified factors concerned with the ability to direct moving stimuli to a set destination and D'Oliveria (2004) discusses factors pertinent to relative arrival time and intercept judgement.

Despite not intentionally investigating dynamic spatial ability, Roff (1952), employing a factor analysis on motion picture tests, identified a factor he classified as 'Movement Time'. There were six variables loaded on this factor in his factor analysis, five were designed to measure participants' ability to identify movement direction and minimal movement, to judge destination, to record simultaneous movement combinations and to integrate partial impressions observed through a moving slot into a single visual scheme or pattern. A sixth variable which loaded on the factor was a static variable designed to measure objectivity of perception. While not classified as dynamic spatial ability, Roff's tests appear to be measuring similar factors to those in the more contemporary studies.

Taking cognizance of Larson's (1996) work, it should be recognised that dynamic spatial factors involve different mental operations to static spatial factors. As such, the literature review identified five factors which should be considered as unique dynamic spatial factors:

- **Directional Judgement:** The ability to judge the direction of a moving stimulus and identify its destination or to give direction to a stimulus when provided with a destination.
- **Speed Judgement:** The ability to judge the speed of a moving stimulus and identify arrival times.
- **Movement Detection:** The ability to detect minimal movement and to identify the direction of such movement.
- **Dynamic Patterns:** The ability to identify similar dynamic patterns within an array of dynamic stimuli.
- **Dynamic Memory:** The ability to remember partially observed moving stimulus and identify it within a whole pattern.

## Conclusion and Recommendations

This paper provides an insight into some of the work which has aided the formation of our current understanding of spatial ability. With the recognition of the significant correlation between high levels of spatial ability and success in engineering education it is argued that a theoretical framework which comprehensively illustrates the cognitive factors within this domain merits development. Four considerations for such a framework have emerged as a result of the literature review described in this paper and are offered as guiding principles to underpin further developments in this area. The significance in developing a comprehensive spatial ability framework which is underpinned by these principles lies in its potential to frame a common conception of the domain and to narrate a common language. For engineering education specifically, these advances could help initiate further investigation into the causation behind spatial ability and success in the discipline. Uncovering this causation could then initiate many scientific developments. For example, a single robust measurement instrument could be developed which would elicit a holistic profile of a persons' level of spatial ability. If further research identified specifically which factors were significant to engineering education this instrument could then be tailored to measure these factors and allow for such data to be gathered for engineering education students. Further to this a scientifically proven spatial development intervention could be designed which could develop higher levels of competency in the discipline which would ultimately lead to increased performance and further related benefits. Finally, it should be noted that as our understanding of the nature of spatial ability develops, further factors within the domain may be uncovered. Such developments are welcomed as this understanding could lead to many significant discoveries and developments in engineering education.

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