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Problematising And Framing Spatial Research In Engineering Education

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PROBLEMATISING AND FRAMING SPATIAL RESEARCH IN ENGINEERING EDUCATION

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ABSTRACT

Spatial research has experienced a surge in popularity across the global community in recent years, with an undeniable rise in the favourability of spatial thinking approaches in academic and higher education settings. An engineer’s spatial ability is dependent on their capacity to engage a set of cognitive skills to visualise, reason and communicate spatial relations between objects and space. With the recent growth in popularity around spatial research, new spatial terms are frequently introduced resulting in a definitional overlap between terms and ideas. This may sometimes result in a lack of clarity regarding spatial terms and definitions, with the definitions of such terms varying amongst the literature. The eight most researched spatial terms over the last ten years are included in this study: *Spatial Ability, Spatial Skills, Spatial Intelligence, Spatial Visualisation, Spatial Literacy, Spatial Reasoning, Spatial Factors and Spatial Thinking.* A review of literature supported the unpacking of spatial terms and related research and the subsequent synthesis of the same. Particular focus centred on the various definitions and conceptualizations of these terms, as well as the contexts in which they are used to improve the accuracy, validity, and value of spatial analysis and its potential applications across different fields and disciplines. This paper aims to unpack and synthesise the various interpretations and dimensions of spatial competencies in the body of international research, ensuring that the pertinent research information is more readily accessible to practicing engineering educators.

1 INTRODUCTION

Spatial competency skills are widely regarded as a fundamental component of cognitive development, with primary links to problem solving and working memory (Ishikawa and Newcombe 2021). Working memory is a limited-capacity system that stores and manipulates information temporarily for complex tasks such as comprehension, learning and reasoning (St Clair-Thompson et al. 2010). One of the system's key components is the visuospatial sketchpad, which allows people to mentally represent and manipulate visual and spatial information such as mental images, maps, and spatial relationships between objects. It additionally facilitates mental rotation and recall of visual details such as colours and shapes. The ability to hold and interact with visuospatial representations has been identified as a nonverbal intelligence indicator of success in professions such as engineering and architecture (Baddeley 2003). This is supported with the research conducted in recent years highlighting that there is a direct correlation between one’s academic achievement, retention rates and spatial ability (Sorby et al. 2018). Coupled with the fact of spatial skills being malleable (Lane and Sorby 2022) and the disappointing fact that students worldwide are entering third-level education with underdeveloped spatial skills (Uttal et al. 2013), it is imperative that we allow our educational systems to be more efficient and sustainable, so to allow every student equal opportunities to develop these spatial skills.

This paper aims to analyse the literature base relating to spatial competencies in Engineering Education, to develop a framework around the use, implementation and definitions of various spatial terms as used throughout the literature between 2012 and 2022 inclusive.

2 METHODOLOGY

2.1 Approach

To clarify the area for new and experienced researchers the most prevalent terminology in the field of spatial research is examined and identifies how each term is used in context to determine a universal definition for each. A three-step approach was implemented in this review:

1. Determine the scope of spatial research over the last ten years in engineering education.
2. Identify the most frequently employed spatial terminology used by researchers.
3. Emphasise links and unique differences between terms, thus determining a universal definition for each.

2.2 Dataset

A series of searches were conducted on the Web of Science, to determine the data selection for this study as shown graphically in *Figure 1*. The 'advanced search tool' was used to identify studies for review while inclusion and exclusion criteria were carefully considered to ensure that the workload was manageable and that a large enough scope was provided to identify trends in the research. As a result, the search was refined to include only articles or review articles. Furthermore, only studies in the field of engineering were considered to narrow the search to ensure that the resulting papers were also sufficiently representative. On February 9, 2022, the first electronic search of this study was conducted on the Web of Science database details of which are highlighted in *Figure 1.*

2.3 Screening

Of the 83,941 papers, the top fifty cited papers were selected and screened by both title and abstract for the next stage of the review. Each paper was examined thoroughly and for every spatial term mentioned an analysis was conducted on how it was used in the paper and the paper's context. For example, both David Uttal and Nora Newcombe believe that spatial skills are distinct from other sets of skills and that depending on the scale of the task, different cognitive processes are engaged (Uttal et al. 2013; Newcombe et al. 2013). From the outlined review (*Figure 1*), eight key terms were identified; *Spatial Ability, Spatial Factors, Spatial Intelligence, Spatial Literacy, Spatial Reasoning, Spatial Skills, Spatial Thinking, and Spatial Visualisation.* An independent search for each key term ("code") was conducted through the Web of Science database under the same conditions as the first search. The following are the results of papers including the relevant term in their writing; *Spatial Ability* (n=171), *Spatial Thinking* (n=59), *Spatial Skills* (n=106*), Spatial*

Intelligence (n=28), *Spatial Literacy* (n=4†), *Spatial Visualisation*‡ (n=93), *Spatial Reasoning* (n=85) and *Spatial Factors* (n=75).

All articles from the search (n= 433) were downloaded into the Zotero reference management software where duplicate articles were removed (n=356) and papers were organised by term into sub folders. For the final phase of screening, the top 20§ cited papers from each code were included in the review (n=152).

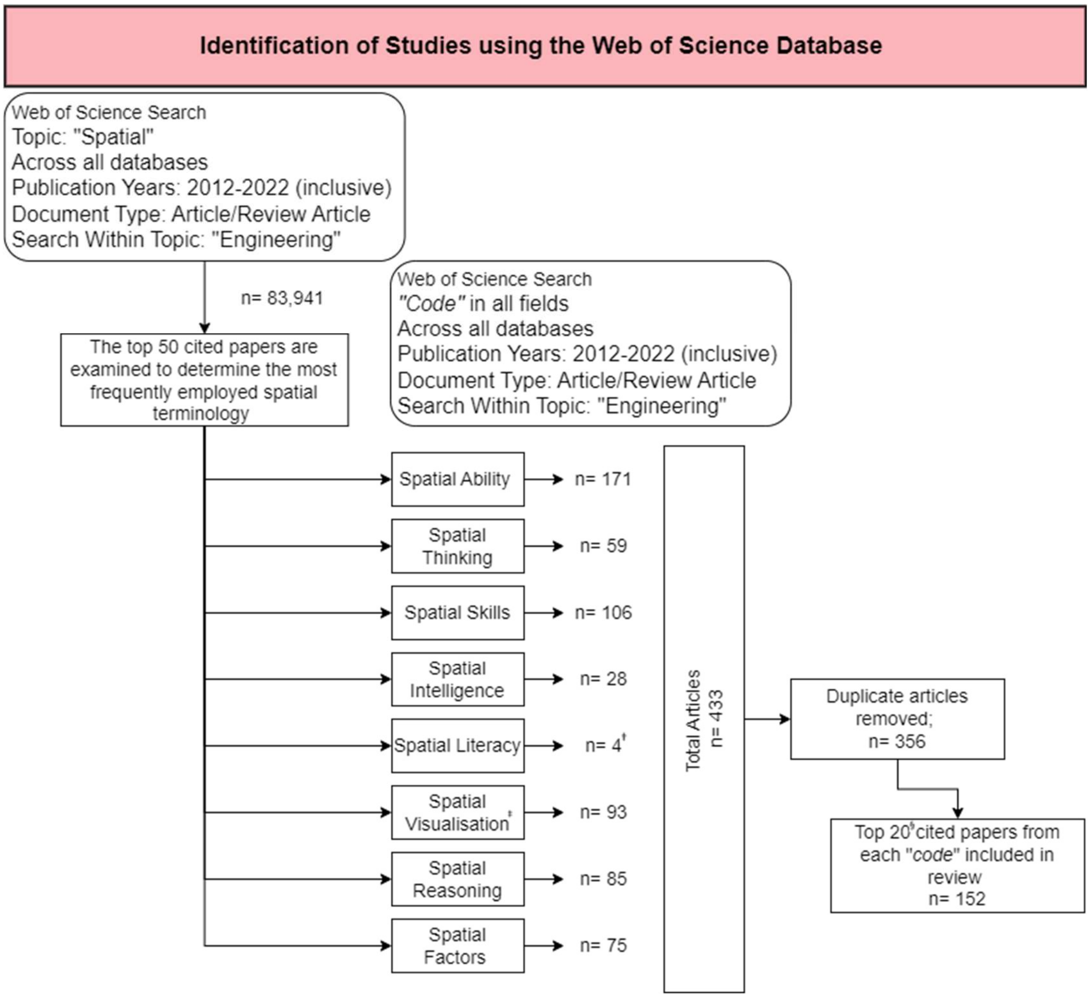

Figure 1. Flow Diagram illustrating the procedure for identifying the spatial terms that occur most frequently in Engineering Education research.

3 RESULTS

The results of this study are summarised in *Figure 3* which highlights the definitions of terms and the key similarities and differences between the areas of spatial research in engineering education. With the consistent increase in peer-review

† *In the case of Spatial Literacy all papers were included.*

‡ *For "Spatial Visualisation", "Spatial Visualization", was also included in the search.*

§ *For terms >30 results, all papers were included.*

publications in spatial research in the last decade it is paramount that all researchers are well versed in the varying areas and the related terms. This flowchart serves as a comprehensive tool which can be used by both experienced and new researchers mapping a sustainable approach towards an area of spatial research.

3.1 Spatial Ability & Spatial Factors

(Carroll 1993) highlighted that 'spatial ability' is found to be a term of common usage in both academic and everyday conversation, yet its precise definition is seldom considered or clarified. Researchers have the same basic conception of the term with it being described as 'one's ability to comprehend and mentally manipulate objects, shapes, and space in order to navigate and interact with the physical world and solve problems' (Uttal et al. 2013; Buckley et. al 2018; Ganley et. al 2014) However for a true definition, its context must first be considered. Language used in relation to spatial ability attainment is important to note with research most often conducted in relation to the enhancement of one's ability after exposure to spatial interventions. For example, if you were to measure a participants 'spatial ability' before exposure, you would call this measurement their 'innate spatial aptitude' in comparison to after exposure, their 'learned spatial ability' (Buckley et al. 2018). Consequently, it is evident that to define spatial ability you must first explore the factors of which are relevant to its context. Factor analysis is known to be one of the most common methods used to describe the underlying structure of intellect and is specifically implemented through 'paper and pencil tests' allowing for exploration of relationships between variables and the development of a greater understanding of complex data sets (Hegarty et al. 2005)

The Cattell-Horn-Carroll (CHC) theory is widely regarded as being the primary framework of human intelligence and cognitive factors, which in turn aids in defining spatial ability based on its factor structure, as shown in *Figure 2* (Schneider and McGrew 2012).

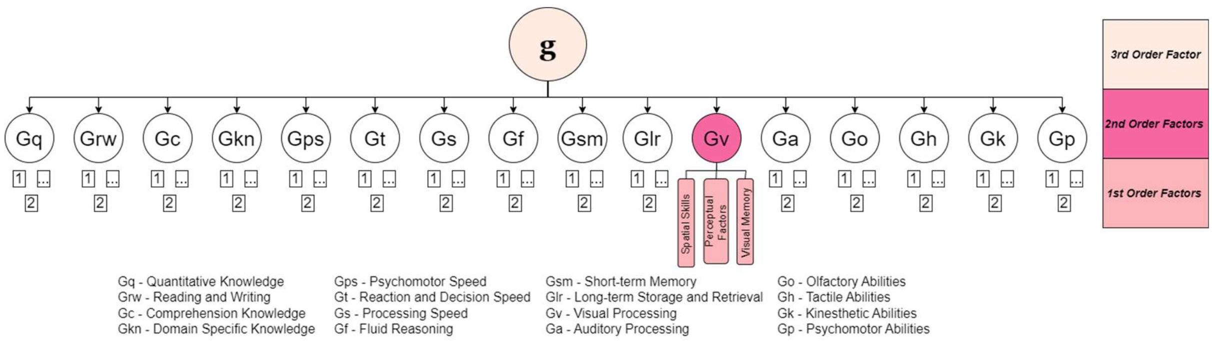

Figure 2. Cattell-Horn-Carroll Theory adapted from (Buckley et. al 2018)

Figure 2 illustrates this hierarchical theory which contains three different orders of factors. The third-order factor (g) at the top of the hierarchy represents one's general intelligence (Spearman 1904) which then filters into sixteen second-order factors representing primary mental abilities. Spatial ability is expressed as one of these second-order factors and is referred to as *Gv*, visual processing. Eleven first-order factors load directly onto *Gv* which are broadly grouped into three categories: spatial skills, visual memory, and perceptual factors. These first-order factors are more commonly known as spatial factors to aid in differentiation between other first-order factors in the theory and are primarily concerned with the various environmental and cognitive factors that contribute to the development and enhancement of spatial skills. Spatial factors are also independent of semantic knowledge as we can understand and manipulate objects in space without relying on previous knowledge or information. Uttal *et al*. (2013) recognises these spatial factors as being related to spatial skills, thus solidifying its definition as a person's ability to mentally manipulate objects and visualise spatial relationships such as distance and size. There are both dynamic factors, relating to movement, and static spatial factors relating to fixed spatial information, with the interaction of both being important in developing one's spatial ability. For navigating complex environments, those with strong static spatial abilities rely on maps, whereas those with dynamic spatial abilities rely on real-time sensory input from the environment to navigate.

3.2 Spatial Skills & Spatial Visualisation

There is a direct link between spatial skills and spatial visualisation with almost all studies examining spatial skills dependant on using visualisation as a predictor of capacity. Over the years, clarification of its importance is evident in studies across the board; Newcombe (2013) identifies it as being directly related to the ability to interpret graphs and solve problems and Uttal (2012) explores its use in imagining the geometries of cut sections of three-dimensional objects and structures. There are also instances in which an object may be described as a flat surface (navigational map), requiring a greater level of skill to comprehend and visualise the described object (Lane and Sorby 2022). Spatial skills can be differentiated into two broad categories, small and large scale, with each category respectively drawing on different cognitive processes. Researchers have recently discovered a strong positive correlation between spatial skills and success in Science, Technology, Engineering and Mathematics (STEM) education (Cheng and Mix 2014; Lowrie et al. 2017). The development of spatial skills however continues to be a significant "blind spot" in many educational systems despite this significant research, with students worldwide entering third-level education with underdeveloped spatial skills (National Research Council 2006). These skills are malleable however, and can be improved in formal educational settings both directly and indirectly (Lane and Sorby 2022; Uttal et al. 2013). Some researchers also make reference to a 'visuospatial' ability which can be described as a specific type of spatial ability which emphasises visual processing skills (Lowrie et al. 2017; Aguilar Ramirez et al. 2020). Similarly, visuospatial thinking refers to the cognitive process of mentally manipulating and transforming visual and spatial information to solve problems (Hegarty and Stull 2012).

3.3 Spatial Intelligence

According to Gardner's multiple intelligence theory, first put forth in 1993, intelligence is not one unified skill but rather a group of different skills or intelligences that each function somewhat independently of one another. (Gardner 1993) claims that each person has a special combination of these intelligences, and that different people may excel in various fields. This theory, which contends that people can develop their strengths in various areas to achieve success in a variety of fields, has been extensively used in education and career development. Spatial intelligence can therefore be described as a person's ability to think in three-dimensional space, visualise objects in different orientations and create mental images from information provided from the physical world. While spatial intelligence and spatial thinking are related, they are not the same thing. Individuals with high spatial intelligence may not necessarily have strong spatial thinking skills, and vice versa. However, the two concepts are often interrelated, as individuals with strong spatial thinking skills may be better able to apply their spatial intelligence to real-world tasks.

3.4 Spatial Thinking, Spatial Reasoning & Spatial Literacy

(Smith 1964) describes spatial thinking as being a fundamental skill within the STEM domain with its core links to spatial awareness, spatial reasoning, and spatial literacy. We often describe spatial thinking as a collection of cognitive skills used to represent, analyse and reason about objects, space and their relationship with the environment and in 2012, (Newcombe and Shipley) proposed a spatial thinking typology based on two dichotomous factors. The theory proposes that there are two different ways in which people can engage with spatial information: intrinsically or extrinsically. Intrinsic spatial information refers to information that is related to the objects or features themselves, such as the shape, size, and location of objects in a space, and can be processed independently of the viewer's position and orientation in relation to the objects. In comparison, extrinsic spatial information refers to information that is related to the viewer's position and orientation in relation to the objects and involves considering the viewer's perspective and the way the objects are arranged in relation to the viewer. Newcombe's theory has important implications for education and training in spatial thinking. By understanding these individual differences, educators and trainers can tailor their instruction to better meet the needs of learners with different spatial thinking abilities. Spatial thinking provides the foundation for spatial reasoning. The ability to mentally manipulate and visualize spatial information is critical for solving problems that require spatial reasoning. Both skills are important in many areas of life, from academic pursuits to everyday activities such as driving or navigating a new city.

Spatial literacy was found to be the least used term in spatial research over the last ten years with only four results noted. From these papers, spatial literacy can be commonly known as the ability to understand and interpret spatial information and to think abstractly and critically about spatial relationships. (Moore-Russo et al. 2013) made sense of this by identifying the three core components of spatial literacy which subsequently, add to research in the area without direct mention: spatial reasoning, spatial visualisation, and communication.

4 CONCLUSIONS AND FUTURE WORK

Spatial research is a complex area that has grown from the psychology discipline into the broader educational research arena in recent years. The complexity of the area demands careful unpacking, synthesis, and consideration especially at the beginning of research studies that aim to examine different nuances of how humans think about spatial concepts. This paper serves as a guide for both new and experienced researchers, through the clarification of core spatial terms ensuring that pertinent literature data is easily accessible to all. As seen from the flow diagram (*Figure 1*), there is not an equal distribution of research among areas, highlighting the need for researchers to look deeper into their area of spatial research. One reason as to why spatial ability studies have been published more often is due to the availability of objective metrics (such as mental rotations testing and paper folding testing) and the ease in which these can be analysed. Conversely, spatial thinking is much more nuanced and somewhat subjective in its measurement and accordingly it would require the use of interviews, observations to examine sketching skills, reflection on past experiences, beliefs, and values – as a result of this, there are less studies that have reported on such research. It is critically important that we, as educators, understand and appreciate these nuances in competencies to allow for spatial learning to be embraced fully into our educational systems resulting in a more sustainable, spatial education for all.

Figure 3 highlights synthesis of theory relating to spatial research in a mapping format, with the intention of encouraging both experienced and new researchers to understand what spatial learning entails more holistically. This framework also provides researchers with a comprehensive tool that can be used in mapping a sustainable approach towards an area of spatial research at any stage in their research careers. From conducting this study, developing and utilising the theoretical map of spatial research, future work will focus on the area of spatial factors and spatial ability with reference to the gender gap in engineering.

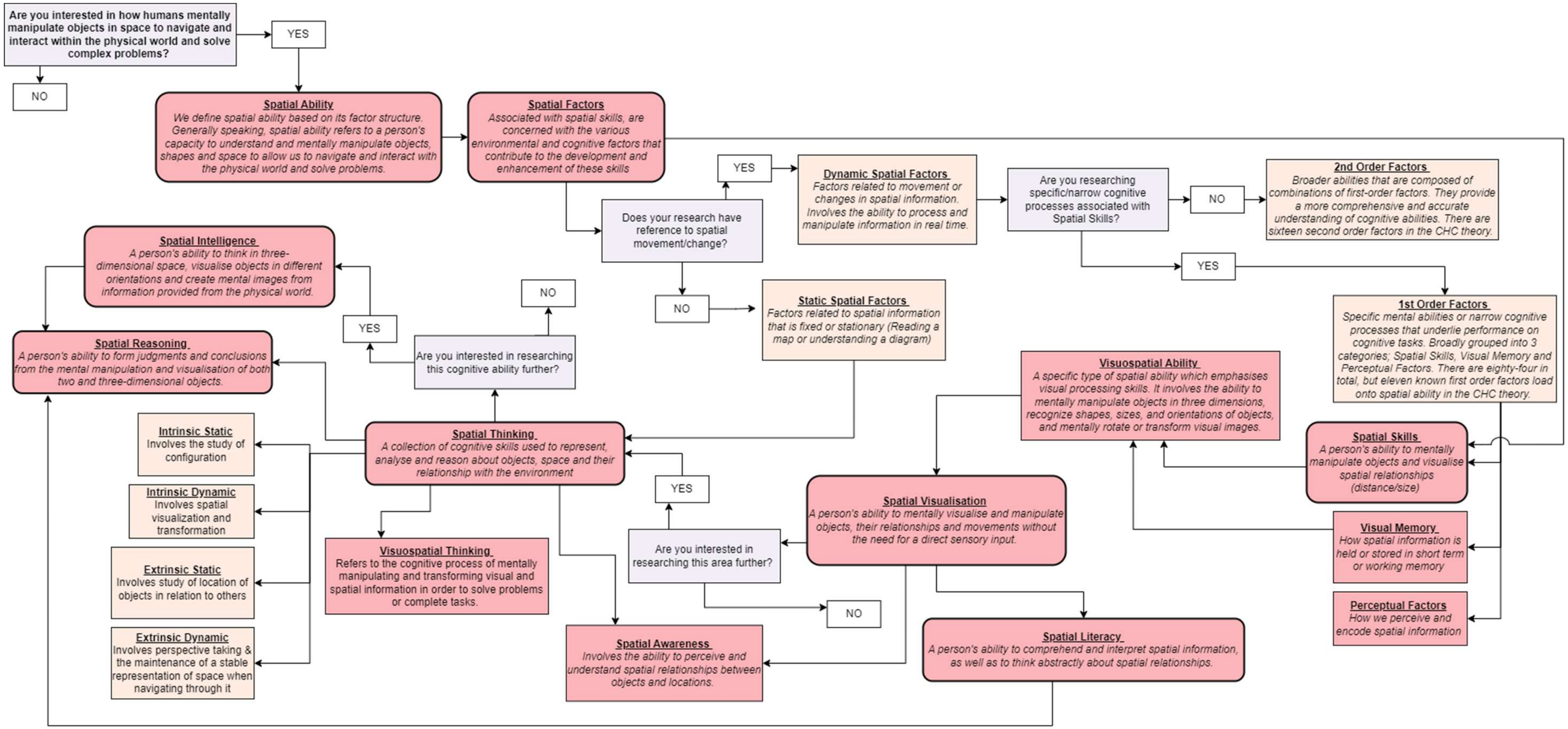

Figure 3. Theoretical Mapping of Spatial Research (2012-2022)

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