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Work in Progress: Review of Working Memory, Spatial Ability, and Spatial Anxiety in Engineering Problem-Solving

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Introduction

One often overlooked barrier to engineering education and subsequent careers is spatial ability. Underdeveloped spatial abilities can hinder student success in prerequisites such as calculus and physics and further courses in the engineering curriculum [1]. In this paper, we review the literature on working memory, spatial abilities, spatial anxiety, and the relationships between them while focusing on the context of engineering problem-solving. Spatial ability is part of a hidden curriculum: it is relevant in engineering education but not explicitly and consistently acknowledged or explained by instructors. In the novice state, learners frequently call upon spatial thinking for problem-solving. With experience gained, learners become more familiar with discipline problem types and rely less on their spatial strategies. Experts' accumulation of disciplinary knowledge allows the generalization of algorithms and rules, which enable problem solutions without any mental spatial manipulations. Many engineering educators are unaware of their expert blind spot. This literature review aims to synthesize spatial abilities, spatial anxiety, and how they interact through working memory to affect engineering problem-solving.

Engineering Problem-Solving

Problem-solving is a nonroutine activity that requires mental representation. In cognitive psychology, solving problems is theorized to begin with a representation phase, which draws on linguistic, semantic, and schematic knowledge, followed by a solution-phase in which core competencies, guided by strategic knowledge, are applied [2]. Spatial ability is key to the problem representation phase. Duffy, Sorby, and Bowe found that spatial ability was relevant to using linguistic knowledge, translating assignment statements, translating relational statements, and selecting schemata from long-term memory. For example, a problem from their 2020 journal article states, "When blood samples are centrifuged, the blood separates into two distinct layers—one made up mainly of plasma and the other made up of red blood cells. A sample of blood was put in a flat bottomed test tube with a diameter of 3 cm. When the blood sample was added to the tube, it filled the tube to a depth of 7.5 cm. After centrifuging, the red blood layer was 1.5 cm deep. What is the volume of the plasma in the sample?" [3][3][3, pg. 430]. Here, linguistic knowledge includes comprehending "blood samples" as a noun. Translating relational statements involves the solver linking the flat bottomed test tube before and after centrifuging. An example of an assignment statement to be translated is that the diameter of the test tube is 3cm. Semantic knowledge, or common knowledge, is activated when considering the test tube's shape to select the mathematical formula for a cylinder's volume. The final component of the representation phase is the application of schematic knowledge, where the solver must identify and select a mathematical schema from long-term memory (LTM) for the problem or find it in the problem statement. Duffy, Sorby, and Bowe found that representation is related to spatial ability problems with several assignments and relational statements. Their study shows that spatial ability plays a crucial role in engineering education that is not limited to visualization of imagery but extends to thinking during problem-solving. Hence, to understand engineering problem-solving, we need to understand spatial abilities and how they are affected by anxiety due to limitations of working memory.

Working Memory

Working memory (WM), a component of information processing theory, is a helpful framework for explaining spatial ability, spatial anxiety, and their interaction. In information processing theory, a human can be characterized as an information processing system, which encodes input, operates on that information, stores and retrieves it from memory, and produces output in terms of actions. Our sensory register transfers information to WM, where those perceptions are worked on and integrated with data from LTM or permanent memory. Due to these parallel requirements, WM has a limited capacity [4]. Researchers demonstrated that a single memory system could not account for all kinds of temporary memory, so they fractionated WM based on separately held verbal and visual-spatial representations. The central executive, also known as an executive function or executive functioning, manages these representations. WM demonstrates processing limits, storage limits, and temporal decay. A central attentional controller and two subsystems make up the WM hierarchy [4]. The central executive (CE) oversees the phonological loop and the visuospatial sketchpad. The content of the material determines the distinction between the two subsystems. The phonological loop is where linguistic and numerical information is temporarily stored while simultaneously processed, while the visuospatial sketchpad is where 2D and 3D representations are temporarily stored while simultaneously processed. The central executive can integrate the two subsystems, link them with LTM information, and manipulate the resulting model [5].

The episodic buffer was added to the model in 2000, making it the multicomponent model of WM. The episodic buffer is assumed to be a limited capacity storage system capable of temporarily holding and manipulating information registered in a multidimensional code [6, 7]. The term episodic reflects its capacity to hold integrated episodes that extend both spatially and temporally. It is a buffer because it offers a multidimensional code that allows information from different subsystems to be integrated and linked to LTM. Such a multidimensional capacity tends to be computationally demanding, hence the buffer's limited capacity [8]. The buffer is assumed to be controlled by the CE, using conscious awareness as an effective retrieval strategy [9-11]. The episodic buffer's prominent feature is information chunking. Chunking is where storage capacity increases by integrating several disparate features into a single whole [12]. The episodic buffer involves the more complex aspects of chunking, such as integration, whereas the executive function is applied when creating new chunks from previously unrelated features.

Miyake and colleagues found three spatial factors (spatial perception, spatial visualization, and spatial relations) differed concerning the central executive's degree of involvement [13]. Spatial visualization showed the highest involvement, and spatial perception showed the lowest. All three spatial factors require a substantial degree of visuospatial storage, but the maintenance of visuospatial representations ties to executive functioning or controlled attention. The study also showed that executive functioning and visuospatial WM variables could fully explain the intercorrelations between the three spatial ability factors. This study is a prime example of the usefulness of WM in characterizing the nature of cognitive processes such as spatial abilities.

Spatial Ability

Spatial cognition is the generating, storing, retrieving, and transforming of visual information. Since its original conceptualization, the literature recognizes that this construct includes a multiplicity of factors [14]. The Cattell-Horn-Carroll (CHC) theory proposes a hierarchical structure of statistically related factors for human cognitive ability. The factor representing general intelligence is in the third (top) stratum of the system. The second stratum contains 16 factors or elements, which are broad abilities. In the first stratum, there are 84 factors, which load through factor analysis on the second stratum factors. CHC theory posits spatial ability as a second-order factor: visual processing. Visual processing can generate, perceive, analyze, synthesize, store, retrieve, manipulate, transform, and think with graphic patterns and stimuli [15]. Schneider and McGrew compactly defined visual processing as the ability to use "simulated mental imagery (often in conjunction with currently perceived images) to solve problems" [16]. Visual processing has eleven factors: visualization (VZ), speeded relations (SR), closure speed (CS), the flexibility of closure (CF), visual memory (VM), spatial scanning (SS), serial perceptual integration (PI), length estimation (LE), perceptual illusions (IL), perceptual alternations (PN), and imagery (IM) [16].

CHC theory does not include dynamic spatial abilities and focuses on static spatial abilities. These differ primarily by the presence or absence of an object's movement. Traditional paper and pencil tests dominate spatial ability assessments [17]. This testing modality only evaluates static spatial abilities; evaluating dynamic skills requires modern technology. Pellegrino identified dynamic spatial skills using computerized tasks of arrival time [18, 19]. These tasks include participants determining when a moving object will reach a target or intercept tasks in which a viewer manipulates two moving objects to arrive at a target simultaneously. These are called time-to-contact judgments. For example, the ability to catch a football, play a video game or perform as an air traffic controller would require dynamic spatial skills.

Spatial cognition reveals another difference when comparing the scale involved in spatial abilities. Large-scale and small-scale spatial abilities (LSSA and SSSA, respectively) are two spatial problem types where spatial transformation occurs. These transformations vary according to the kind of reference frame - viewer or object-based. LSSA involves an egocentric spatial transformation due to having a viewer-based reference frame. Representative examples of LSSA include navigation and spatial orientation. These spatial skills are tied to the sensory-motor system and require a spatial change from the central axis of one's body. Here individuals encode object locations concerning the front/back, left/right, and up/down axes of their body [13, 20]. SSSA typically contains mental rotation problems in an object-based reference frame. These spatial abilities involve allocentric transformations that require a spatial change of one object relative to another object or point external to the viewer.

SSSA divides into two main subcategories – spatial perception and spatial visualization. Spatial perception involves determining spatial relationships related to gravitational or kinesthetic cues [21]. Spatial visualization (SV) usually requires complex and multi-step mental transformation/rotation of two or three-dimensional figures. Tests of SV measure apprehending, encoding, and mentally manipulating spatial forms [22]. Mental rotation is an important case of spatial visualization requiring a cognitive process to transform or rotate two- or three-dimensional (3-D) objects [17]. Spatial visualization tasks require multi-step manipulation and a possibility of more than one strategy to reach the problem's solution [22].

In contrast, mental rotation is a single step and a primary strategy to get to a solution. Spatial visualization includes the capacity to plan for the necessary steps beforehand and monitor one's thought process during problem-solving. This ability to monitor one's problem-solving process increases spatial visualization's link to executive control.

Anxiety & Spatial Content

Anxiety disrupts working memory, though it is unknown how this disruption occurs [23]. Researchers speculate that anxiety leads to restricting the capacity of WM by interference with task-relevant processes, though the literature is mixed. The literature considers anxiety by type and component of anxiety.

There are two types of anxiety – state and trait. State anxiety is a negative emotional response due to negatively demanding or harmful situations or stimuli. In contrast, trait anxiety refers to individual differences, meaning a general predisposition to appraise many situations or stimuli as threatening. Individuals with higher trait anxiety are more likely to have higher state anxiety [24-26].

The anxiety component has two categories: worry (e.g., anxious thoughts) or emotionality (affective arousal; e.g., tension, nervous, or jittery). Worry links to the phonological loop, while emotionality links with the visuospatial sketchpad [27]. However, some studies connect both components to the phonological loop and the visuospatial sketchpad [28]. Liu et al. investigated the interaction of emotion and working memory. Their findings showed that verbal working memory's updating function was significantly longer in positive emotion than in neutral or negative emotion. Spatial working memory's updating function was substantially longer in the negative emotion than the positive emotion [29]. In verbal or spatial WM, the delay of using the updating functions disrupts the simultaneous corresponding processing.

Spatial anxiety is fear or apprehension when engaged in spatial thinking. Performance anxieties such as computer anxiety, math anxiety, spatial anxiety, or test anxiety are all state types. While investigating gender differences in way-finding strategies, Lawton focused on spatial anxiety [30]. In 2018, researchers further developed a Spatial Anxiety Scale (SAS), and Geer built upon that to form the modified spatial anxiety scale (M-SAS) [30, 31]. M-SAS consists of a four-factor structure of spatial anxiety with a total of 47 items. The factors these items load to are imagery, mental manipulation, scalar comparison, and navigation. This instrument encompasses large and small-scale spatial abilities grounded in the literature [32].

Spatial anxiety in engineering problem-solving merits further study due to a gap in the literature. Hsi, Linn, and Bell state in their paper *The Role of Spatial Reasoning in Engineering and the Design of Spatial Instruction*, "…the social context of spatial strategy instruction often encourages anxiety and frustration rather than learning" [33]. Engineering educators can provide learning environments that foster positive social interaction in the classroom in addition to content knowledge and procedural knowledge. This work contributes to enabling engineering educators to be mindful of spatial abilities and anxiety related to spatial information in engineering.

Conclusion

We reviewed the literature on information processing theory, spatial abilities, anxiety, and their relationships. Spatial ability includes visualization, organizing information sources, and mapping between a source and a new format representing the same original information. Encountering nonroutine information places a high demand on the working memory system. Spatial information, working memory processing, and/or storage can trigger state anxiety, which can delay the updating function of visuospatial working memory. Spatial abilities are more vital in the novice learning stage, so it may be difficult for instructors with years of experience to identify what task-relevant information is perceptually obscure to novices accurately. As researchers and educators, we need to be more mindful of spatial abilities since evaluating spatial abilities is implicit in contemporary curriculum and instructional design. An expert's blind spot contributes to instructional decisions that exclude spatial information or strategies that may benefit novice learners. Due to spatial ability's relationship with translating linguistic knowledge into schematic knowledge, instructors could consistently focus on the specific step of translation during problem representation in multiple contexts [3]. The problem solver could be made aware of these knowledge components and identify them in problem statements. Translating between linguistic and schematic knowledge, along with the practice of creating spatial visualizations, should lead to higher success rates in engineering problem-solving.

References

[1] C. Dawson, "Tackling Limited Spatial Ability: Lowering One Barrier into STEM?," *European Journal of Science and Mathematics Education,* vol. 7, no. 1, pp. 14-31, 2019.

[2] R. E. Mayer, *Thinking, problem solving, cognition*. New York, NY: W. H. Freeman, 1992.

[3] G. Duffy, S. Sorby, and B. Bowe, "An investigation of the role of spatial ability in representing and solving word problems among engineering students," *Journal of Engineering Education,* vol. 109, no. 3, pp. 424-442, 2020, doi: 10.1002/jee.20349.

[4] A. D. Baddeley and G. J. Hitch, "Working Memory," in *The Psychology of Learning and Motivation: Advances in research and theory*, vol. 8, G. h. Bower Ed. New York: Academies Press, 1974, pp. 48-79.

[5] A. Baddeley, "Fractionating the Central Executive," in *Principles of Frontal Lobe Function*, D. T. Stuss and R. T. Knight Eds. New York, NY: Oxford University Press, 2002, pp. 246-260.

[6] A. Baddeley, "The episodic buffer: a new component of working memory?," *Trends Cogn Sci,* vol. 4, no. 11, pp. 417-423, 2000.

[7] A. Baddeley, "The phonological loop and the irrelevant speech effect: Some comments on Neath (2000)," *Psychonomic Bulletin & Review,* vol. 7, no. 3, pp. 544-549, 2000.

[8] J. Hummel, "The binding problem " in *The MIT Encyclopedia of the Cognitive Sciences* R. A. Wilson and F. C. Keil Eds.: MIT Press, 1999, pp. 85-86.

[9] A. Baddeley, "Working memory and conscious awareness," in *Theories of memory.*, A. F. Collins, S. E. Gathercole, M. A. Conway, and P. E. Morris Eds. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc, 1993, pp. 11-28.

[10] A. Baddeley and J. Andrade, "Working memory and consciousness: An empirical approach.," in *Theories of Memory*, M. Conway, S. E. Gathercole, and C. Cornooldi Eds., II ed.: Psychology Press, 1998, ch. 1, pp. 1-24.

[11] A. D. Baddeley and J. Andrade, "Working memory and the vividness of imagery," *Journal of experimental psychology: general,* vol. 129, no. 1, p. 126, 2000.

[12] G. A. Miller, "The magical number seven, plus or minus two: Some limits on our capacity for processing information," *Psychological review,* vol. 63, no. 2, p. 81, 1956.

[13] A. Miyake, N. P. Friedman, D. A. Rettinger, P. Shah, and M. Hegarty, "How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis," *J Exp Psychol Gen,* vol. 130, no. 4, pp. 621-640, Dec 2001, doi: 10.1037/0096-3445.130.4.621.

[14] F. Galton, "Generic Images," *Nineteenth Century,* vol. 6, pp. 187-169, 1879.

[15] D. P. Flanagan and S. G. Dixon, "The Cattell-Horn-Carroll Theory of Cognitive Abilities," in *Encyclopedia of Special Education: A Reference for the Education of*

Children, Adolescents, and Adults with Disabilities and Other Exceptional Individuals, 2013.

[16] J. Carroll, *Human cognitive abilities: A survey of factor-analytical studies*. New York: Cambridge University Press, 1993.

[17] J. Buckley, N. Seery, and D. Canty, "Spatial cognition in engineering education: developing a spatial ability framework to support the translation of theory into practice," *European Journal of Engineering Education,* vol. 44, no. 1-2, pp. 164-178, 2019, doi: 10.1080/03043797.2017.1327944.

[18] J. W. Pellegrino, E. B. Hunt, R. Abate, and S. Farr, "A computer-based test battery for the assessment of static and dynamic spatial reasoning abilities," *Behavior Research Methods, Instruments, & Computers,* vol. 19, no. 2, pp. 231-236, 1987.

[19] E. S. Quellmalz and J. W. Pellegrino, "Technology and testing," *science,* vol. 323, no. 5910, pp. 75-79, 2009.

[20] B. Tversky, J. Bauer Morrison, N. Franklin, and D. J. Bryant, "Three Spaces of Spatial Cognition," *The Professional Geographer,* vol. 51, no. 4, pp. 516-524, 1999, doi: 10.1111/0033-0124.00189.

[21] M. C. Linn and A. C. Petersen, "Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis," *Child Development* vol. 56, no. 6, pp. 1479-01498, 1985.

[22] D. F. Lohman, "Spatial abilities as traits, processes, and knowledge," in *Advances in the psychology of human intelligence*, vol. 4, R. J. Sternberg Ed. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc., 1988, ch. 6, pp. 181–248.

[23] A. J. Shackman, I. Sarinopoulos, J. S. Maxwell, D. A. Pizzagalli, A. Lavric, and R. J. Davidson, "Anxiety selectively disrupts visuospatial working memory," *Emotion,* vol. 6, no. 1, pp. 40-61, Feb 2006, doi: 10.1037/1528-3542.6.1.40.

[24] R. Hembree, "Correlates, Causes, Effects, and Treatment of Test Anxiety," *Review of educational research,* vol. 58, no. 1, pp. 47-77, 1988.

[25] R. Hembree, "The Nature, Effects, and Relief of Mathematics Anxiety," *Journal for Research in Mathematics Education,* vol. 21, no. 1, pp. 33-46, 1990.

[26] H. Miller and J. Bichsel, "Anxiety, working memory, gender, and math performance," *Personality and Individual Differences,* vol. 37, no. 3, pp. 591-606, 2004, doi: 10.1016/j.paid.2003.09.029.

[27] M. W. Eysenck and M. G. Calvo, "Anxiety and Performance: The Processing Efficiency Theory," *Cognition and Emotion,* vol. 6, no. 6, pp. 409-434, 1992/11/01 1992, doi: 10.1080/02699939208409696.

[28] T. P. Moran, "Anxiety and working memory capacity: A meta-analysis and narrative review," *Psychological Bulletin,* vol. 142, no. 8, pp. 831-864, 2016, doi: 10.1037/bul0000051.

[29] X. Liu *et al.*, "Effect of Emotion States on the Updating Function of Working Memory," presented at the 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) 2018.

[30] I. M. Lyons, G. Ramirez, E. A. Maloney, D. N. Rendina, S. C. Levine, and S. L. Beilock, "Spatial Anxiety: A novel questionnaire with subscales for measuring three aspects of spatial anxiety," *Journal of Numerical Cognition,* vol. 4, no. 3, pp. 526-553, 2018.

[31] E. A. Geer, "The Development and Construct Validation of the Revised Spatial Anxiety Scale " Masters of Science, Department of Psychology, Florida State University 2019.

[32] D. H. Uttal and C. A. Cohen, "Spatial Thinking and STEM Education: When. Why and How?," in *The Psychology of Learning and Motivation*, vol. 57, (Psychology of Learning and Motivation, 2012, pp. 147-181.

[33] S. Hsi, M. C. Linn, and J. E. Bell, "The Role of Spatial Reasoning in Engineering and the Design of Spatial Instruction," *Journal of Engineering Education,* 1997.