A Review of Spatial Ability Research

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Abstract

Spatial ability research has been approached from several psychological vantages since its beginnings in the late 1800s. This contribution attempts a summation of spatial ability research, beginning with a historical vignette and a major section on each psychological approach including the psychometric, developmental, differential and information processing approach. Of importance is what each approach has contributed to our knowledge of spatial ability.

WHY IS SUCH A REVIEW NEEDED?

In the fall of 1996, Miller provided an excellent historical review of spatial visualization research. His article chronicled the various approaches to spatial visualization literature documented in past issues of the Engineering Design Graphics Journal. Miller's article is a well-known (and well-referenced) starting point for thesis or dissertation research projects on the topic. However, there is much literature outside the bounds of the Engineering Design Graphics Journal. To complement Miller's work, this contribution details spatial ability research from various branches of psychology and other fields. Essentially, this article documents seminal pieces of literature that, when combined with Miller's historical review, provide a more holistic view of the field of spatial ability research.

THE BEGINNINGS OF THE RESEARCH

With implications for nearly every technical field, spatial ability continues to be an active thread of research found throughout many disciplines. As early as 1880, Sir Francis Galton reported on his experimental inquiries into mental imagery. Since that time, researchers have defined spatial ability in numerous ways, contending over its constituents and creating various methods for measuring it.

The chronology of spatial ability research can be broken into four major periods of activity. Table 1 shows this author's chronology and the associated themes or approach. While an assortment of sources provide in-depth historical accounts (Carroll, 1993; Eliot & Smith, 1983), a brief historical vignette seems appropriate to begin this contribution; setting the stage for a review of the major research traditions and their contributions.

Table 1

Chronology of Research with Themes and Approach

Date Range	*Themes and Approach*
1880 - 1940	Acknowledgement of a spatial factor separate from general intelligence through psychometric studies
1940 - 1960	Acknowledgement of multiple space factors through psychometric studies; emergence of myriad spatial assessments
1960 - 1980	Psychometric studies into cognitive issues; emergence of developmental and differential research
1980 -	Effect of technology on measurement, examination, and improvement; emergence of information processing research

A Historical Vignette

Although credit belongs to Galton (1880, 1911) as being the initiator of the research, publications with a spatial focus did not emerge until the early 1920s. Contributions from 1880 to 1940 acknowledged and defined spatial ability as separate from general intelligence. Through the work of Thorndike (1921), Kelley (1928), El Koussy (1935), and Thurstone (1938), researchers regarded spatial ability as a capacity separate from the general intelligence factor (g) defined by Spearman (1927).

From 1940 to 1960, researchers focused their energies on defining what comprised spatial ability, but not without difficulty. While a few researchers attended to this area, many deemed the ability unimportant. Many viewed spatial functioning as a "lower ability" due to its practical manifestations. Adding to this undervaluation, confusion within the burgeoning community created additional difficultly (D'Oliveira, 2004; Lohman, 1979a). Because of differing factor analysis techniques and the use of different spatial ability tests, researchers adopted contradictory names and definitions for spatial factors (Cooper & Mumaw, 1985). They also included conflicting numbers of factors (see Hegarty & Waller, 2005). Nevertheless, spatial testing obtained an important foothold due to large-scale assessment conducted in the Army Air Forces (Guilford & Lacy, 1947). By the end of this period, researchers agreed that spatial ability was not unitary and many spatial tests were available (see Eliot & Smith, 1983).

From 1960 to1980, several divergent approaches to spatial ability research emerged. Witkin (1950) and Gardner's (1957) psychometric studies examined cognitive issues such as learning styles. Developmental studies by Piaget and Inhelder (1971) examined how spatial ability develops through childhood to adulthood. Differential researchers focused on areas of difference in spatial ability, particularly as it relates to differences across gender. Work by Maccoby and Jacklin (1974) serves as the much-referenced contribution in this area. Due to the varied approaches during this period, knowledge of spatial ability–its development and differentiation–blossomed.

While prior research themes have continued, from 1980 to today researchers have focused on the impact of technology on measurement, examination, and improvement of spatial ability. In addition, much attention has been turned toward understanding spatial ability from the information processing perspective.

From this 100-year history of research one thing remains clear: spatial ability is a set of complex, cognitive abilities about which there are still many questions. Each of the research approaches provides a unique contribution. The following sections will delve into these research approaches, providing an outline of significant endeavors and contributions.

PSYCHOMETRIC RESEARCH

One of the initial challenges posed to spatial research was distinguishing it from the general intelligence factor. Two major groups with differing views pursued intelligence research. Research in Britain followed Spearman in focusing on intelligence as a single factor, whereas research in the U.S. viewed intelligence as composed of multiple factors. The former work was pursued by Spearman (1927), Burt (1949), and Vernon (1950) and the latter work was conducted by Thurstone (1950), Cattell (1971), and Guilford (1967).

Initially researchers had difficulty distinguishing spatial ability factors from intelligence because several of the spatial factors load quite heavily on general intelligence (spatial visualization tests, for example). Typically intelligence has been viewed hierarchically and taxonometrically, with the former emerging first (Gustafsson, 1988). Figure 1 shows a basic hierarchical view of the structure of human abilities and the juxtaposition of spatial abilities (Smith, 1964).

As shown in Figure 1, when mental tests are analyzed using factor analysis, the first factor to be extracted typically corresponds to g. Once g is

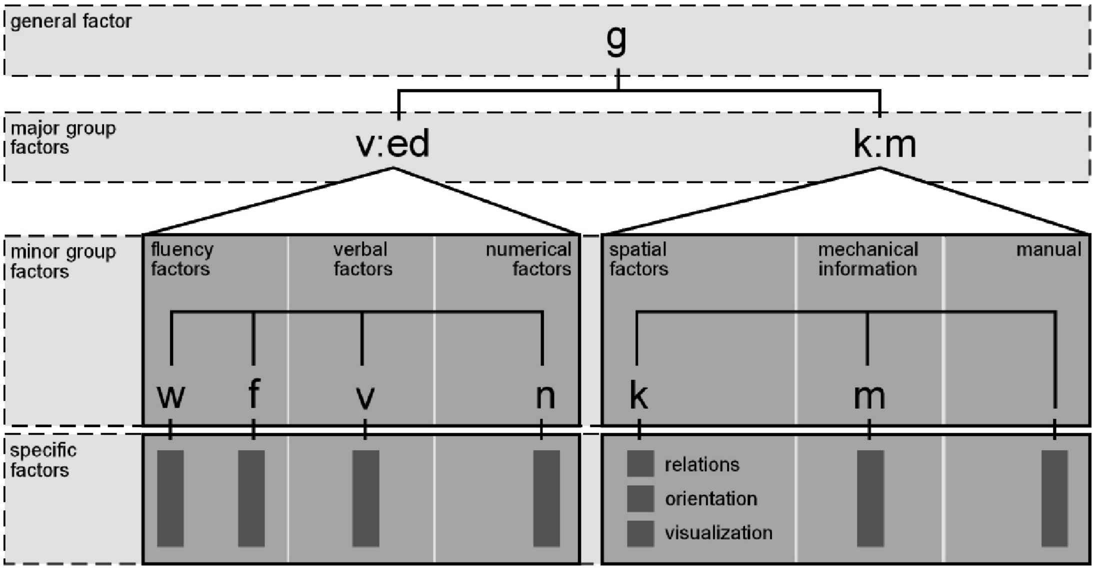

Figure 1. Hierarchical structure of human abilities (Smith, 1964).

removed, the tests typically fall into two groups: verbal-numerical (v:ed factor) and the spatial-mechanical-practical (k:m factor). If there are enough tests in the battery being used, the two subgroups can be divided further into minor factors, such as verbal, numerical, or spatial and manual.

Scientific and empirical work that is more recent has attempted to define hierarchical models of intelligence and specific aspects of those models (Snow & Lohman, 1989; Snow, Kyllonen, & Marshalek, 1984). Due to its extensive inclusion of datasets, the best-known contemporary factor analytic survey is Carroll (1993).

Of importance to this review was Carroll's discussion of a hierarchical "three-stratum theory" of ability that "could be accommodated within, or show correspondences with, radex theories that assume hierarchical structures" (Carroll, 1993, p. 654). Carroll identified three hierarchical strata (narrow, broad, and general) into which cognitive abilities fell. Radex theories, the earliest of which Carroll credits to Guttman (1954), are typically taxonomic (rather than hierarchical). Figure 2 shows an example of the radex model of

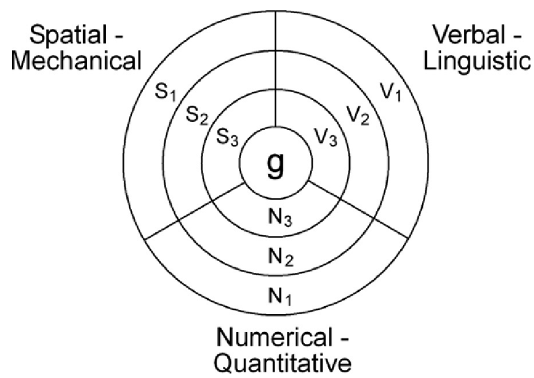

Figure 2. Example of the radex model of intelligence (Guttman, 1954).

intelligence, which demonstrates the positioning of spatial ability in juxtaposition with verbal and mathematical ability.

The three abilities shown in Figure 2 have psychological importance and can predict occupational and educational success. While Carroll (1993) discussed arguments against this "three-stratum theory," the sheer magnitude of the data and subsequent studies present a compelling argument for support of the radex model. However, some research acknowledges that hierarchical and radex models can mesh quite well and even complement each other (Snow, et. al, 1984).

The Acknowledgement of a Spatial Factor

The published identification of spatial ability was a 1921 paper by Thorndike. He drew an important distinction among three broad classes of intellectual functioning, as opposed to Spearman's "singular view" of intelligence. He argued that standard intelligence tests measured only "abstract intelligence." While Thorndike included abstract intelligence in his own threefold model, he highlighted that "mechanical" and "social" intelligence were equally important. Thorndike's publication serves as the starting point for published spatial ability research. Through his work, he defined "mechanical intelligence" as the ability to visualize relationships among objects and understand how the physical world worked. Thorndike called for measures for these other types of intellect and set the stage for all the spatial ability research that would follow.

Afterward, Kelley (1928) and British contemporary El Koussy (1935) also challenged the verbal-based definition of intelligence. El Koussy examined spatial intelligence and, consequently, was instrumental in developing methods for measuring it. El Koussy found evidence for the existence of a factor "K," which he defined as the ability to obtain and utilize visual spatial imagery. Kelley went further with his notions that the manipulation of spatial relations was another distinct factor within spatial ability.

Similarly, Thurstone (1938) studied primary mental abilities and defined a "space" factor that represented the ability to operate mentally on spatial or visual images. His theory was that intelligence was made up of several primary mental abilities rather than a single, holistic factor. He was among the first to propose and demonstrate these factors through his Multiple Factors theory. The theory identified seven primary mental abilities, which included associative memory, number facility, perceptual speed, reasoning, spatial visualization, verbal comprehension, and word fluency. This theory was the basis for intelligence tests that yield a profile of individual performance from several ability scores, rather than the single mark.

Multiple Space Factors

Through subsequent research and using abstract nomenclature, Thurstone (1950) identified three primary spatial factors within spatial ability. Literature that followed replaced Thurstone's scientific designations with more descriptive terms (Smith, 1964). Mental rotation (S1) was defined as the ability to recognize an object if moved to different orientations or angles. Spatial visualization (S2) was the ability to recognize the parts of an object if they were moving or displaced from their original position. Spatial perception (S3) emerged as the ability to use one's body orientation to relate to questions regarding spatial orientation.

Modern Psychometric Research

Modern research has proposed additional factors of importance in spatial ability. The first of these is a result of Carroll's definition of spatial factors (1993). Carroll defined a hypothetical imagery factor that is "the ability in forming internal mental representations of visual patterns, and in using such representations in solving spatial problems" (p. 363). Burton and Fogarty (2002) set out to determine if this factor existed. In their research, they did find that imagery could be a reliable component when the testing of this ability is related to something other than normal, everyday imagery. Yet they also recommended further study and confirmation from other studies.

An additional factor being examined is what Pellegrino and Hunt (1991) term "dynamic spatial ability." D'Oliveira (2004) stated that dynamic spatial ability is "the ability to deal with moving elements and relative motion" (p. 20). This factor was first examined by Hunt, Pellegrino, Frick, Farr and Alderton (1988). D'Oliveira's conclusion was that another way of looking at spatial ability is from a static versus dynamic quality. D'Oliveira acknowledged the general lack of valid tests and made a call for new dynamic ability measures.

DEVELOPMENTAL RESEARCH

The goal of developmental research is to answer questions related to when and how spatial ability develops. Seminal to this area is work by Piaget and Inhelder (1971). They conducted extensive studies with children and developed several spatial tests that are still used today. Developmental research predominately focuses on issues of age, but also delves into neurological issues such as hemispheric specialization.

Spatial Ability and Age

Piaget and Inhelder (1971) stated that spatial ability developed in three phases as the child matures. In the topological space stage, children acquire 2D skills and learn the relationship of objects to one another. During the projective space stage, children learn to work with 3D objects, particularly what objects look like from different vantages (orientation skills) and how objects look when they are rotated (rotation skills). In the third stage, individuals learn to go back and forth between 2D and 3D (the transition from projective space to Euclidean space). Here concepts such as parallelism, proportion, area, volume, and distance are acquired. Although lesser-known, parallel work has been conducted by Bruner (1964) and Werner (1964).

Several studies have focused on developmental issues. Some studies focus on spatial ability differences at various age levels (Battista, 1990; Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990). Others focus on the ages at which different aspects of spatial ability seem most apparent (Salthouse & Mitchell, 1990; Tartre, 1990). Others focus on how spatial ability changes over time (Coleman & Gotch, 1998).

Research in this area has found that age affects spatial ability (Halpern, 2000). Spatial ability improves with age in childhood years (Orde, 1996), but declines with age in adulthood (Pak, 2001). Age-related differences are often a result of differences in processing speed, knowledge, and experience (Salthouse, 1987) and age affecting accuracy in problem solving (Nunez, Corti, & Retschitzki, 1998). Spatial perception, that is, the ability to determine horizontal or vertical dimensions, does not emerge until around age nine (Olson, 1975) but spatial ability sex differences favoring males do exist at prepubertal ages (Vederhus & Krekling, 1996), specifically at seven or eight years of age (Glasmer & Turner, 1995). These differences remain constant to age 18 (Johnson & Meade, 1987). However, sex difference emergence is highly dependent on the type of test (Voyer, Voyer, & Bryden, 1995); there is not a male advantage on all spatial factors. In addition, education can improve spatial ability with ages as young as nine (Rovet, 1983).

While not an exhaustive review of the literature in this area, these conclusions provide a sampling of representative studies. It should be noted that Piagetian tests (i.e., tests of conservation and water-level tests) are not considered direct measurements of spatial ability (visualization, orientation, rotations), even though the abilities they detect are related to spatial ability (Harris, 1978).

Spatial Ability and Hemispheric Specialization

Hemispheric specialization is another area examined by developmental researchers. Here researchers strive to understand brain physiology and its relationship to spatial ability (Rilea, Roskos-Ewolden, & Boles, 2004). There is general agreement that those with right-brain dominance perform better at spatial tasks and have more highly developed spatial abilities (McGlone, 1980). In addition, males are more often right-brain dominant and they mature more rapidly in this area (Harris, 1978).

DIFFERENTIAL RESEARCH

Literature consistently notes the differences in the spatial performance of males versus females, frequently acknowledging male superiority. Maccoby and Jacklin (1974) spawned an incredible interest within this area when they discussed four areas in which sex differences emerge, most notably in spatial ability. In addition to this, several researchers have provided reviews of the sex difference literature (Harris, 1978; Linn & Petersen, 1986; Nyborg, 1983; Voyer, Voyer, & Bryden, 1995).

The differential literature is quite expansive—it appears to be one of the most contested issues in spatial ability research. Generally, in spatial tasks (particularly rotations), spatial perception, mathematical reasoning, and targeting ability, males outperform females. In verbal fluency, perceptual speed, memory, and certain motor skills, females outperform males (Kimura, 1996).

There are also a limited number of studies that indicate that the performance difference between the genders is decreasing, or in some cases, that it does not exist at all (Brownlow, 2001; Lord & Garrison, 1998).

One of the most controversial articles (Caplan, MacPherson, & Tobin, 1985) criticized studies finding sex differences due to construct inconsistency (the definition of spatial ability) and small effect sizes of those studies. However, the response from the community was tremendous in refuting these claims (Burnett, 1986). Responses acknowledged that while effect sizes in most studies are small, it does not trivialize the fact that there is a reliable gender difference.

Sex Differences in Spatial Ability

Sex differences in spatial ability favor males and are nearly "universal across regions, classes, ethnic groups, ages, and virtually every other conceivable demographic variable" (Eals & Silverman, 1994, p. 95). Male superiority is most demonstrative in tasks of mental rotation, with lesser differences evident in orientation and no differences evident in visualization (Harris, 1978; Linn & Peterson, 1986). Most researchers also acknowledge that the sex difference does not reliably appear until after puberty and that, maturation has an effect on spatial development—late maturation is related to high spatial ability (Nyborg, 1983).

These studies usually also acknowledge the affect of hormones on spatial ability. Estrogen negatively affects spatial ability, whereas testosterone has a non-linear affect on spatial ability (Kimura, 1996; Moffat & Hampson, 1996). Some of these studies go so far as to state that hormones are the overarching reason for the emergence of sex differences, while others focus on the "real-time" effect of hormones.

Reasons for Sex Differences

Researchers hypothesize several reasons for sex differences. For example, Eliot and Fralley (1976) mentioned sex-linked recessive genes, child-rearing, educational environments, or culture that could underlie the differences. They also acknowledge that it could be a complex interaction between these as well. As such, most of the literature can be reduced to an argument for biological factors or environmental factors. The next two sections will briefly review some of the studies in the "nature" versus "nurture" debate.

Biological Explanations. Several researchers conclude that the sex differences in spatial ability are a result of biological factors (Bock & Vandenberg, 1968; McGee, 1979a). A variety of studies have shown that spatial ability does indeed have a heritable component (Wilson & Vandenberg, 1978) and many demonstrate that spatial ability is as much (or more) inheritable than verbal ability (McGee, 1979b).

Nevertheless, various biological explanations for sex differences favoring males include overarching hormonal impacts (Nyborg, 1983), a theory on an X-linked recessive gene (Walker, Krasnoff, & Peaco, 1981), as well as an evolutionary theory related to male and female roles (Eals & Silverman, 1994).

Of the posited biological theories, the X-linked recessive gene theory has been a primary focal point. However, one critical article (Boles, 1980) refutes this theory through reanalysis. Boles states that most of the studies showing evidence for this theory used sample sizes that were too small for confidence or yielded statistically insignificant results. Among the articles discussing X-linked recessive genes, this appears to be the only article calling the theory into question.

Regardless of the theoretical vantage, much effort has been put into examination of the biological basis for sex differences. The opposing view is that environment plays the primary role in individual development.

Environmental Explanations. Like biologically based views, researchers have devoted much study to role of environment in the development of spatial ability. This viewpoint purports that cultural (Mann, Sasanuma, Sakuma, & Masaki, 1990), social (Belz & Geary, 1984), sex-role and stereotype (Tracy, 1990), developmental (Tracy, 1990), and educational factors (Harris, 1978) are sources for differences in spatial ability.

Sherman (1967) specifically argued that gender differences in spatial ability exist due to varied experiences–his belief was that environmental differences play a primary role in the development of spatial ability. Several others agreed with this viewpoint (Harris, 1978).

While many of these environmental factors are straightforward, the educational factors that are purported to impact spatial ability development are many. Researchers believe that problem solving strategies and skills (Clements & Battista, 1992; Mislevy, Wingersky, Irvine, & Dann, 1990); mathematical background, achievement, and problem solving ability (Michaelides, 2002; Wheatley, Brown, & Solano, 1994); as well as musical background (Heitland, 2000a; Robichaux & Guarino, 2000) are potential roots for the development of spatial ability, and therefore, the reason for sex differences.

Current Perspectives on Sex Difference Origins. While evidence for gender or environment (or an interaction of the two) is not conclusive, it is clear that they both play some role in the development of spatial ability and therefore, the differences that are exhibited (Harris, 1978). Several researchers advocate overcoming arguments that one or the other is the only agent, and instead, acknowledging that both biological and environmental factors contribute to the development of sex differences (Brosnan, 1998; Casey, Nuttall, & Pezaris, 1999). As stated by Vandenberg, Stafford, and Brown (1968), "It is time for psychologists to cease ignoring either source of variation [biological or environmental] and proceed with full recognition that the two are highly interdependent (p. 153)."

INFORMATION PROCESSING RESEARCH

One final area of research focus is in the area of information processing research. As noted by Kyllonen, Lohman and Woltz (1984), "Information processing research attempts to trace the flow of information through the human cognitive system from the time some stimulus is initially perceived to the time an over response is taken" (p 17-18). Its goal is to understand the processes involved in cognition, their order, and the speed at which they occur.

Thus, many of these researchers have examined the speed and efficiency in spatial processing and its impact on the development of spatial ability. Several studies found that speed and efficiency of performing mental transformations does explain a certain degree of variation of spatial skills (Poltrock & Agnoli, 1986; Salthouse et. al, 1990). Studies in this area have also examined strategies in solving spatial problems (Gages, 1994). They found that high spatial ability individuals have a wider range of strategies and are better at determining when to use a particular strategy. However, both high and low ability individuals switch strategies (Kyllonen et. al, 1981). Such studies have also examined real-world scenarios, rather than test-based examinations (Juan-Espinosa, Abad, Colom, & Fernandez-Truchaud, 2000). The information processing perspective has also been used as a lens through which to view differential studies (Lohman, 1984).

SUMMARY

Each of the research perspectives described in this contribution has added significantly to the body of knowledge on spatial ability. Psychometric studies have been instrumental in defining spatial ability and its factors. Developmental studies have provided knowledge about how and when spatial ability develops. Differential literature expounds the differences between genders and the information-processing literature has focused on strategies and processes.

In attempting to understand the spatial phenomenon, most of these studies aim at learning more about spatial ability so that we can better tap into and development it. Spatial ability affects many fields and disciplines and is a predictor for success in many areas of life. It is hoped that this contribution will aid those beginning a career in spatial ability research by providing an overview to the broad research that already exists on the topic. While spatial ability research is as broad as it is deep, there is still much work to be done in this area.

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