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Creativity and Technical Innovation: Spatial Ability's Unique Role

Harrison J. Kell, David Lubinski, Camilla P. Benbow, and James H. Steiger
Department of Psychology and Human Development, Vanderbilt University

Abstract

In the late 1970s, 563 intellectually talented 13-year-olds (identified by the SAT as in the top 0.5% of ability) were assessed on spatial ability. More than 30 years later, the present study evaluated whether spatial ability provided incremental validity (beyond the SAT's mathematical and verbal reasoning subtests) for differentially predicting which of these individuals had patents and three classes of refereed publications. A two-step discriminant-function analysis revealed that the SAT subtests jointly accounted for 10.8% of the variance among these outcomes ($p < .01$); when spatial ability was added, an additional 7.6% was accounted for—a statistically significant increase ($p < .01$). The findings indicate that spatial ability has a unique role in the development of creativity, beyond the roles played by the abilities traditionally measured in educational selection, counseling, and industrial-organizational psychology. Spatial ability plays a key and unique role in structuring many important psychological phenomena and should be examined more broadly across the applied and basic psychological sciences.

Keywords

spatial ability, creativity, human capital, STEM, intelligence, cognitive ability

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When a diverse group of intellectual leaders in the psychological sciences—Howard Gardner, Lloyd G. Humphreys, Roger N. Shepard, and Richard E. Snow—all agree on the importance of something, it gets one's attention. But when their consensus also speaks to the urgent social need for identifying and developing talent in science, technology, engineering, and mathematics (STEM) to promote intellectual innovation in global markets (Friedman, 2007; National Science Board, 2010; U.S. Department of Commerce, 2012), something more than mere attention is warranted. For several decades, these leaders in developmental-humanist, differential, experimental, and educational psychology have emphasized—each in his own way—that spatial ability offers something important and unique to the understanding of learning, work, and creativity (Gardner, 1983, 2011; Gohm, Humphreys, & Yao, 1998; Humphreys, Lubinski, & Yao, 1993; Shepard, 1978; Snow, 1999). They also have argued that tests routinely used in college admissions (e.g., the SAT), although valid assessments up to a point, fail to measure a dimension of cognitive abilities that is of crucial real-world significance. They have suggested that assessing spatial ability could help to correct for this.

Over the past 20 years, a number of large-scale longitudinal studies (e.g., Wai, Lubinski, & Benbow, 2009) have offered evidence that these scholars, as well as others (Lohman, 1988, 1996; Newcombe, Uttal, & Sauter, 2013; Uttal & Cohen, 2012; Uttal et al., 2012), are at least partly correct. Spatial ability seems to play a unique role, relative to mathematical and verbal reasoning abilities, in predicting a variety of outcomes in educational and occupational settings (Gohm et al., 1998; Gottfredson, 2003; Webb, Lubinski, & Benbow, 2007).

The purpose of the study reported here was to move beyond traditional learning and work outcomes and examine the hypothesis that spatial ability plays a unique role in the development of creative products. According

Corresponding Author:
David Lubinski, Department of Psychology and Human Development, Vanderbilt University, Nashville, TN 37203
E-mail: david.lubinski@vanderbilt.edu

to Simonton (2012), a product can be considered creative if it is deemed novel, useful, and surprising (i.e., not obvious) by expert judges (e.g., patent reviewers, peer referees). Therefore, we aimed to test whether spatial ability predicts not only the assimilation and use of *preexisting* knowledge, but also the creation of *new*, innovative knowledge.

One reason creativity and innovation are difficult to study longitudinally is that few people in the general population create products deemed creative and innovative by experts. Because of low base rates, large samples are needed to generate findings with statistical stability and real-world generalizability, especially given how many different ways there are to develop products that experts evaluate as creative. For this investigation, we used a population within which the base rate for a variety of concrete forms of creativity far exceeds that of the general population: intellectually precocious adolescents within the top 0.5% of ability for their age group. The last detailed follow-up of these participants was based on a survey administered when they were age 33 (Shea, Lubinski, & Benbow, 2001) and focused exclusively on their educational and occupational outcomes. In the present study, more than 30 years after their initial identification in the late 1970s, and more than a decade since the follow-up in the late 1990s (Shea et al., 2001), participants were classified according to whether they had published a refereed article or obtained a patent by 2012. Results from cognitive-ability tests administered to these participants more than 30 years earlier were used to ascertain whether spatial ability adds incremental validity (beyond that provided by SAT assessments of mathematical and verbal abilities) to the prediction of these outcomes.

Method

Participants and measures

Participants were 13-year-olds drawn from Cohort 2 of the Study of Mathematically Precocious Youth (SMPY; Lubinski & Benbow, 2006), a planned 50-year longitudinal study of intellectual talent. Between 1976 and 1978, they were identified through talent searches. The criterion for inclusion was a score of at least 500 on the mathematics section of the SAT (SAT-M) or at least 430 on the verbal section (SAT-V); scores at this level put participants in the top 0.5% in cognitive ability for their age group. A few months after their identification, participants attended summer residential programs for gifted adolescents at Johns Hopkins University, where they completed additional assessments, including the Differential Aptitude Test (DAT; Bennett, Seashore, & Wesman, 1974). In this study, as in Shea et al. (2001), a spatial-ability composite score was calculated by equally weighting and summing scores on two DAT subtests: Mechanical Reasoning and Space Relations. Composites such as these "tap a basic ability in spatial visualization" (Carroll, 1993, p. 324). The sample of 393 males and 170 females was 69% Caucasian, 6% Asian or Pacific Islander, 1% African American, and 1% other (23% of participants did not report their race-ethnicity).

Information about each individual's refereed publications and patents was collected using Harzing's (2007) Publish or Perish program in late 2011 and early 2012. A participant was designated as an author of a scholarly publication if he or she was listed as sole author or coauthor of at least one article published in a peer-reviewed journal (see Table S1 in the Supplemental Material available online for examples of the journals). Identified publications were sorted into three categories: arts, humanities, law, and social sciences; biology and medicine; or STEM. A participant was flagged as holding a patent if he or she was certified as sole inventor or coinventor of at least one patent.

Design

This study utilized the group-membership approach to examine remote criteria (Humm, 1946). Humphreys et al. (1993) explicated the logic of this approach for evaluating the construct validity of psychometric assessments, and it has been used for decades (Wai et al., 2009). Because many aspects of life are ipsative, the choice to take one developmental path often precludes taking others. When one achieves an exceptionally rare accomplishment, or an "ultimate criterion" (Thorndike, 1949, pp. 120–127), it typically reflects a protracted series of critical decisions, investments, and sacrifices. Exceptional accomplishments in one area frequently preclude exceptional accomplishments in others, so that relatively distinct criterion groups may be established. Such groupings are useful for uncovering precursors to different developmental trajectories, which lead to qualitatively different accomplishments.

If young adolescents who go on to produce different types of noteworthy creative products can be differentiated by psychometric assessments at an early age, we wanted to capture the specific ability differences that facilitate these different forms of creativity. This would help in determining the substantive significance of the findings, beyond statistical significance (Lykken, 1968; Meehl, 1990). Although our focal aim was to ascertain the added value of spatial ability—relative to mathematical and verbal reasoning—for predicting qualitatively distinct creative outcomes, we wanted to use an approach that would uncover the unique roles of all three abilities and highlight how they give rise to different manifestations of creativity. A three-dimensional graphic approach using Cartesian coordinate planes met these requirements.

First, both SAT-M and SAT-V scores were standardized across the entire sample of participants to have means of 0 and standard deviations of 1.0. Scores on the Mechanical Reasoning and Space Relations subtests of the DAT were standardized separately and summed, and the resulting spatial-ability composite was then standardized to have a mean of 0 and a standard deviation of 1.0.

Next, each criterion group's data on mathematical, spatial, and verbal ability were plotted in three dimensions as an *ellipsoidal confidence region* (see, e.g., Fox, 2008, p. 203; Morrison, 1967, p. 121). For ease of visualization, each ellipsoid was set up such that its location in each dimension was equivalent to a unidimensional plot of the group's mean in that dimension plus or minus 1 standard error.[1] To the extent that these ellipsoids occupy different regions in the space defined by mathematical, spatial, and verbal abilities, they indicate that age-13 assessments portend developmental differences. More ultimately, this application has the potential to reveal the differential promise associated with contrasting patterns of exceptional human talent identified at an early age.

Data matrix

Out of 563 participants, 27 had publications in the arts, humanities, law, or social sciences; 35 had publications in biology or medicine; and 65 had STEM publications. For analytic purposes, participants who earned patents and also had publications (n = 32) were placed in the relevant publication category; only the 33 participants who were exclusively patent holders were placed in the patent criterion group.

Results

Figure 1 presents the core findings; the panels show three rotations of the same data in three-dimensional space. These rotations illustrate how all three abilities isolate the four criterion groups and place them in different locations within the three-dimensional space that the abilities define. For completeness and added scale, these plots also include an ellipsoid for the remainder of our participants, those who did not achieve one of the four creative accomplishments we analyzed. Table S2 in the Supplemental Material provides each group's mean and standard deviation for each ability measure. In each panel of Figure 1, the bivariate means of each group are projected on the front and side graphic surfaces, so these values can be located and compared across groups.

The figure reveals that the groups occupy different regions of intellectual space. Moreover, all three ability dimensions play a role in distinguishing the creative outcomes in a psychologically meaningful way. All three publication groups scored above the full sample's mean for verbal ability, whereas individuals who secured patents (and did not publish) scored below it. The participants with arts, humanities, law, and social sciences publications scored below the full sample's mean for mathematical reasoning; the remaining three groups with creative accomplishments all scored above it. People who published in STEM were quite similar in spatial ability to people who secured patents, but scored 0.37 and 0.57 standard deviations above the patent holders on mathematical and verbal reasoning ability, respectively. What distinguishes the group with arts, humanities, law, and social sciences publications is not that its mean verbal ability is above the full sample's, but that its means for mathematical and spatial ability are appreciably below the full sample's means; this pattern is opposite that of the patent holders.

All three ability dimensions have something to offer with respect to understanding the intellectual architecture supporting qualitatively different creative accomplishments. Spatial ability appears to contribute uniquely to the prediction of different kinds of creative outcomes. To document this statistically, we performed a stepwise discriminant-function analysis on the four criterion groups. In Step 1, mathematical and verbal reasoning ability were entered jointly, and collectively they accounted for 10.8% of the variance among these four groups ($p < .01$). In Step 2, spatial ability was entered as the third variable, and the amount of variance accounted for rose to 18.4%. This additional 7.6% of variance accounted for was statistically significant, $p < .01$.

Discussion

In the 1970s, when SMPY was just over 5 years old, its founder, Julian C. Stanley, decided to experiment with measures not typically used in schools. He was curious about how young adolescents who scored high on college entrance examinations might do on measures of other cognitive abilities—and he hoped to find clues as to how to better meet their needs. Advantageously, however, this move resulted in more; it planted seeds that have grown into potential for informing basic knowledge in the developmental sciences.

This study reveals how students' individual differences operate over time whether or not information about those differences is utilized by opportunity providers or even apparent to the students themselves. Participants knew that doing well on college entrance exams would be important for obtaining acceptance at the universities they wished to attend, but it is unlikely that they ever considered their level of spatial visualization in planning their future or that they were ever selected for learning or

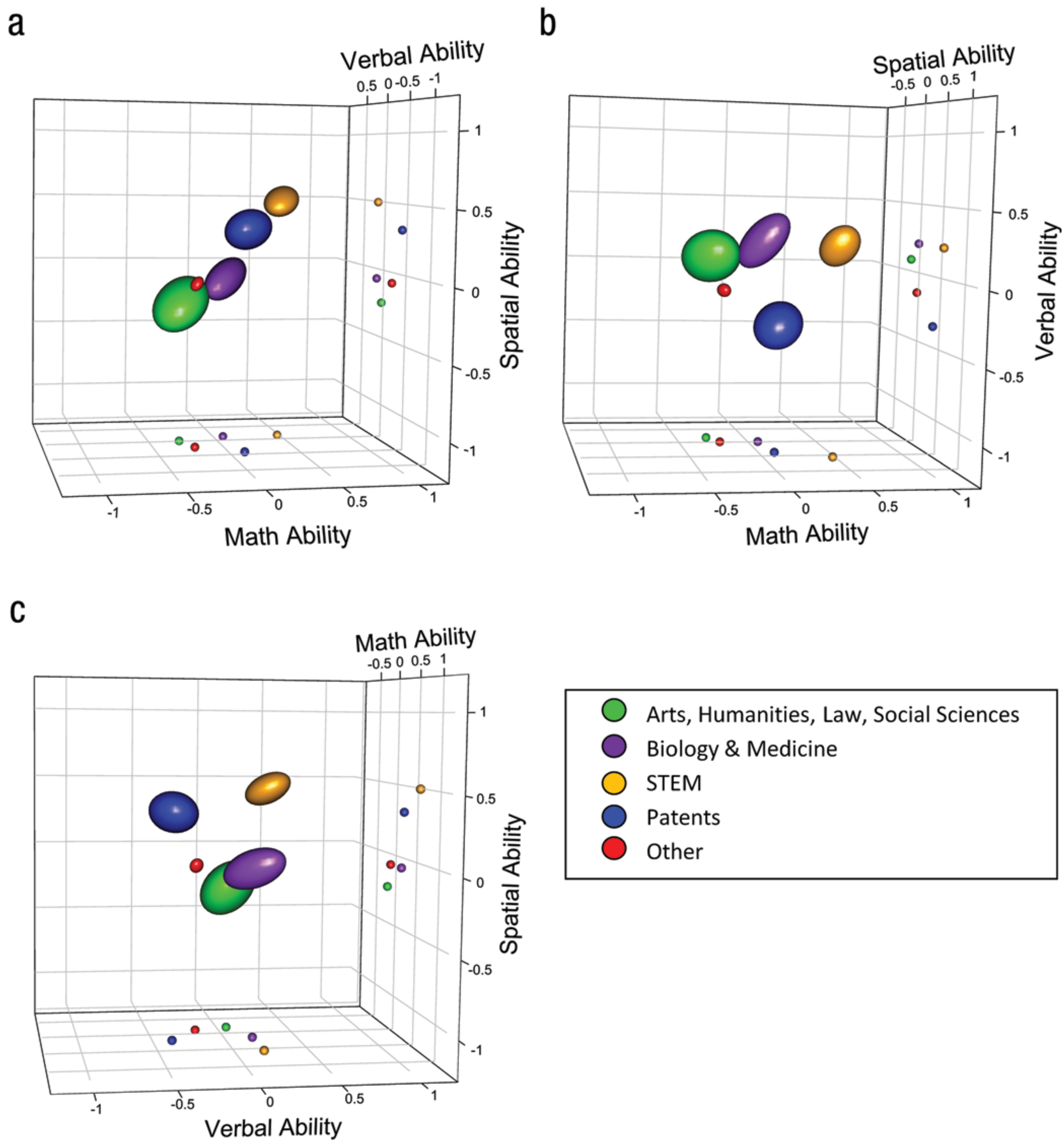

Fig. 1. Confidence ellipsoids showing the locations of the four criterion groups in the three-dimensional space defined by scores for mathematical, verbal, and spatial reasoning ability. The data are rotated such that the graph in (a) shows mathematical ability on the *x*-axis, spatial ability on the *y*-axis, and verbal ability on the *z*-axis; the graph in (b) shows mathematical ability on the *x*-axis, verbal ability on the *y*-axis, and spatial ability on the *z*-axis; and the graph in (c) shows verbal ability on the *x*-axis, spatial ability on the *y*-axis, and mathematical ability on the *z*-axis. The ellipsoids are scaled so that each semiprincipal axis is approximately equal in length to the standard error of the corresponding principal component. Each ellipsoid is centered on the trivariate mean (centroid), and bivariate means are plotted on the bordering grids. The criterion groups were defined as participants with a refereed publication in the arts, humanities, law, or social sciences; a refereed publication in biology or medicine; a refereed publication in science, technology, engineering, or mathematics (STEM); or a patent. In addition, an ellipsoid is shown for participants with none of these creative accomplishments ("other").

work environments on that basis. Yet spatial ability and the intellectual configurations it forms with mathematical and verbal reasoning tell an important story about intellectual development.

Previous 20-year longitudinal findings documented the importance of spatial ability in steering exceptional intellectual talent toward, as well as away from, different educational and occupational environments (e.g., Shea et al., 2001). Regardless of ability level, individuals appreciably more talented in spatial ability relative to verbal ability tend to prefer STEM to the arts, humanities, and social sciences when choosing their favorite high school courses, their undergraduate and graduate majors, and their occupations (Shea et al., 2001; Webb et al., 2007), whereas the inverse is true for talented students whose verbal ability is appreciably more impressive than their spatial ability. The findings reported here, based on data collected in 2011 and 2012, show that the influence of this intellectual pattern extends beyond learning and work settings and into domains of creative production. Collectively, these findings, in conjunction with other extensive longitudinal research on more general populations (Gottfredson, 2003; Humphreys et al., 1993; Wai et al., 2009), support a variety of applied and theoretical considerations.

Modern talent searches exclusively restricted to mathematical and verbal reasoning measures are estimated to miss more than half of students within the top 1% of spatial ability (those who are not within the top 1% in mathematical or verbal reasoning ability but are gifted in spatial ability). This population constitutes an important human-capital resource for developing scientific technological advances (National Science Board, 2010), yet is neglected and underserved by most educational practices. In addition to identifying an underserved population of intellectually talented youth, assessing spatial ability among all intellectually talented youth would provide them, their parents, and the professionals working with them important information about their individuality and relative strengths. This recommendation extends to more general student populations as well. In the words of Snow (1999),

> There is good evidence that [visual-spatial reasoning] relates to specialized achievements in fields such as architecture, dentistry, engineering, and medicine. . . . Given this plus the longstanding anecdotal evidence on the role of visualization in scientific discovery, . . . it is incredible that there has been so little programmatic research on admissions testing in this domain. (p. 136)

Unfortunately, years after this quote appeared, the characterization of spatial ability as an "orphan ability" (Newcombe et al., 2013) remains apt. To help correct for this neglect, researchers may wish to consider using measures outside those typically employed in educational and occupational settings, and longitudinal designs involving remote criteria (Humm, 1946), such as the distinct classes of refereed publications and patents in the present study, to examine the unique role that spatial ability plays.

Our findings support Gardner's (1983) contention that "it is skill in spatial ability that determines how far one will go in science [and technology]" (p. 192). Although modern treatments of creativity and eminence embrace the role of intellectual talent, they seldom do so with sufficient breadth to encompass the three major cognitive abilities examined here. These dimensions hold predictive validity for differential development across the life span (for both likely and unlikely outcomes), as well promise for yielding important findings in future applied and basic psychological research. At more molecular levels of analysis, they may even be useful for focusing inquiry on underlying neurophysiological mechanisms, which give rise to contrasting phenotypic expressions of exceptional intellectual talent (Jung & Haier, 2007).

Conclusion

Spatial ability not only plays a unique role in assimilating and utilizing preexisting knowledge, but also plays a unique role in developing new knowledge. Without spatial ability, the psychological architecture supporting creative thought and innovative production is incomplete—and many applied and theoretical activities in the psychological sciences are destined to be suboptimal.

Author Contributions

H. J. Kell, D. Lubinski, and C. P. Benbow developed the study concept. Age-13 data collection was conducted by C. P. Benbow, and the current data collection was conducted by H. J. Kell. All authors contributed to designing the study and writing the manuscript. H. J. Kell and D. Lubinski conducted an initial series of graphic, multivariate statistical analyses. J. H. Steiger conducted the final series of multivariate analyses and developed the R code for constructing the ellipsoid graphics; he also developed the complete description of the theory and method for constructing these plots provided in How to Construct 3D Plots, in the Supplemental Material available online. All authors approved of the final version of the manuscript submitted for publication.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

Note

1. Readers who would like to reproduce our figures, with our data set, and rotate them in three-dimensional space may do so using the Supplemental Material; instructions are provided in How to Construct 3D Plots, and the necessary R code and supporting files are also provided. These instructions are readily generalizable to other data sets for which three-dimensional-perspective ellipsoidal confidence plots may be appropriate and useful.

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