

# Computer Graphics Education: Where and How Do We Develop Spatial Ability?

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## Abstract

*This contribution provides an overview to the expansive research and literature concerning spatial ability. Its aim is to provide the reader with relevant historical and applied background and to make a call for computer graphics educators to focus on developing the spatial ability of computer graphics majors and non-majors. Spatial ability has broad applicability and provides a necessary area for computer graphics educators to contribute to the student development. Practical activities for the development of spatial ability are also provided.*

K.3.2 [Computer and Information Science Education]: Curriculum

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## 1. Introduction

Computer graphics, whether taught from an artistic, scientific, or technological approach, is an interdisciplinary domain of learning. Foundational to most programs is a course of study that includes some measured mix of focus in art, design, mathematics, computer science, and technology with additional courses sprinkled in to add institutional or departmental flavor. Often program “flavoring” is faculty dependent and based upon individual research agendas.

Underpinning each of these contributing areas of computer graphics education is the ability of a student to visualize, that is, picture and manipulate 2D or 3D representations in the mind for some purpose. It could be argued—particularly in computer graphics—that spatial ability is at least (if not more) important than verbal-linguistic or mathematical-logic skills. While such a statement may be controversial, most computer graphics educators can agree on at least equal importance of verbal-linguistic, mathematical-logic, and spatial-temporal abilities in computer graphics education.

In mathematics and computer science, spatial ability is needed to imagine the visual representations of abstract functions and algorithms. In programming, it is spatial ability that allows one to mentally flowchart the processes involved in a computer application. In art and design, it is spatial ability that let's one consider the impact of color, flow, white space, and other aspects on the composition of a piece. And, in regards to contemporary technologies such as animation and multimedia—in which computer graphics serves a critical function—the dynamic capacity of spatial ability plays a critical role as well.

However, while myriad literature acknowledges the importance of spatial ability and methods for improving it, how many computer graphics curricula actually include a course devoted to developing and refining spatial ability in students? Likely, most faculty assume this ability is developed “throughout the curriculum.” However, based on the literature, it appears that making the assumption that this happens “indirectly” is erroneous.

This contribution briefly touches on the literature, but more importantly, it makes a call for computer graphics educators to consider placing focus and emphasis on direct instruction through activities that develop the spatial ability of students.

## 2. What is Spatial Ability?

One of the things that has plagued spatial ability research is inconsistency in the nomenclature and associated definitions. Many researchers have acknowledged the problems this has caused, not just in communication and understanding, but also in terms of devices for measuring spatial ability and the broad comparison of research results [DOL04], [ES84], [LOH79].

Spatial ability research has been approached from several psychological vantages since its beginnings as early as the late 1800s. The recognition that a distinct space factor existed separate from general intelligence occurred through the work of Kelley [KEL28], El Koussy [ELK35], Thurstone [THU38] and Thorndike [THO21]. Following this, researchers using factor analysis sought to define what composed spatial ability, without regard to how the ability developed or what processes were involved within it. Research by Slater [SLA40], Thurstone [THU50],

Guilford & Lacy [GL47], French [FRE51], and others investigated this.

The research then split into a couple different directions. Several researchers examined spatial ability from an information processing viewpoint, in which they strove to understand the processes involved in the development and use of spatial cognition [CS73], [KYL84], [LOH88], [PH91], [SM71]. Other researchers examined spatial ability from a developmental perspective, looking at the development of spatial ability from childhood [OLS75], [PI71]. And, still others examined spatial ability from a strategy [KWL81; LK83] or differential [CAR93], [HAR78], [LOH84], [LP86], [MCG79], [MJ74], [NYB83], [VVB95] perspective. Interested readers may wish to review historical accounts [CAR93], [ES83], [MCG79], [SMI64].

Peering through the expansive literature one finds that the most generic and commonly accepted definition of spatial ability was provided by Lohman following a comprehensive reanalysis of the seminal research that preceded him [LOH79]. Today it is accepted that spatial ability is not a unitary construct, but rather a collection of factors, even though early research referred to a single space factor. Lohman states that "spatial ability may be defined as the ability to generate, retain, and manipulate abstract visual images (p 188)." In that same report, he acknowledged that spatial ability was composed of three primary factors (visualization, relations, and orientation) and several minor factors. He defined (1) spatial relations as mental rotations and the ability to solve spatial problems quickly, (2) spatial orientation as the ability to relocate the viewer and discriminate between left and right, and (3) spatial visualization as the ability to solve complex spatial problems that facilitate the use of multiple spatial and peripheral factors. More recent work by Carroll has reiterated Lohman's findings in this area and provided a unique viewpoint on intelligence and its composition [CAR93].

### 3. Is Spatial Ability Important?

Literature that highlights the importance of spatial ability abounds. Research from fields ranging from art and education to science and engineering has focused on spatial ability. In these studies, researchers indicate that without spatial ability, success within specific knowledge domains is limited. These domains, while not an exhaustive list, include art [HLY93], architecture [KSK69], [PH89], biology [LOR83], [LOR85], [LOR87], chemistry [BM86], [BOW90], [CBS\*97], [CLB87], [PB87], [SM83], [TIL84], education [GP95], engineering [BW55], [MB90], [MCK68], [PS72], geology [KO96], mathematics [AIK71], [BAL84], [BAT90], [BIS89], [BLH88], [BW89], [FEN74], [FER87], [FS77], [LAN84], [MOS77], [PIA98], medicine [ROC85], music [HBF85], physics [PS84], programming [SMI86], and veterinary science [PLN98].

While researchers draw specific attention to the criticality of spatial ability for success, they acknowledge education's failure to recognize and develop spatial giftedness. In the earliest research, Galton [GAL11] acknowledged:

Our bookish and wordy education tends to repress this valuable gift of nature. A faculty that

is of importance to all technical and artistic occupations, that gives accuracy to our perceptions, and justness to our generalisations, is starved by lazy disuse, instead of being cultivated judiciously in such a way as will on the whole bring the best return (p. 79).

While this statement was made some time ago, not much has changed since Galton wrote it. We are no better at focusing on spatial ability in education today than we were when Galton did his "breakfast table" experiments in imagery. Researchers have acknowledged that spatially gifted individuals are often overlooked at all levels of education. Shea, Lubinski, and Benbow [SLB01] highlight what this means in practical terms:

Given the correlational structure for verbal, quantitative, and spatial abilities, there are obviously large numbers of "high-space" (i.e., spatially talented) students who do not meet the minimum math or verbal criteria for participation in talent searches as they are currently performed. ...using mathematical, spatial and verbal assessments on a stratified random sample of U.S. high school students [HLY93], it can be shown that selecting for the top 3% of verbal-mathematical ability will result in the loss of more than half of the students representing the top 1% of spatial ability! (p 612)

Statements such as these should not only cause us to reexamine how we evaluate "talent," but also what we teach, how we teach it, and how we measure our results. McArthur and Wellner [MW96] issued that the spatial ability of students is poorer today than in the past, likely because there is a little direct focus on spatial ability training. In a longitudinal study, Hilton [HIL85] found that between 1960 and 1980 spatial ability has decreased significantly. Several researchers highlight the need for more domain-specific focus on spatial ability training and its impact in all disciplines [BIS80], [HAB96], [KK98], [KLS84], [LC02], [LOR85], [MCK93], [WEI84], [WES94], [WES98].

### 4. Can Spatial Ability Be Improved?

Research on spatial ability improvement is increasing, but there is still much we do not know. While there are a limited number of studies that question the effect of training on spatial ability [MCF73], [SMI64], [WIT69], the quantity of opposing literature is much greater [ABG02], [BIS78], [BL80], [BN89], [BRI66], [BW55], [CG98], [CS85], [DEB76], [DIX97], [DRA80], [EM77], [EMB92], [FER87], [KK98], [KLS84], [KLW84], [LAN98], [LOR83], [LOR85], [MCK93], [MKC\*75], [PH91], [PS72], [RHO80], [RMK77], [ROV83], [SA91], [SB96], [SS84], [STI75], [WW79]. Authors who question the value of spatial ability training often advocate that such ability is a biological predisposition; an innate ability rather than a trainable skill. However authors such as Miller and Bertoline [MB91] disagree. They stated that spatial ability developed experientially over time, as a result of various environments. While there is a relationship between

nature's effect and experiential nurturing, based on the balance of literature it appears that many different types of interventions can indeed improve spatial ability.

Several researchers have integrated direct instruction into classroom activities with positive results. Typically, such instruction teaches students visualization principles ("picturing objects in the mind") and then mental manipulation of those objects (rotating, moving, and deconstructing). Often such materials are context-specific. An important thing to note is that even limited amounts of spatial training can drastically affect performance. Rovet [ROV83] stated that, "it appears that 12 minutes of instruction was roughly equivalent to three years of untutored development (p. 171)." She acknowledged that development of spatial ability through instruction occurred as a result of very specific, applied activities.

For example, in chemistry activities could relate to the bonding of atoms or other such concepts. In engineering, students may be asked to mentally picture and sketch orthogonal views of three-dimensional objects. And, in mathematics, students could be asked to mentally picture or manipulate a host of algorithms, numerical patterns, or relationships. In each of these cases, spatial ability is directly involved and the educator need only require the student to exercise their mind relative to the content at hand to develop spatial ability.

## 5. Application to Computer Graphics Education

Computer graphics educators are uniquely poised to meet the need for spatial ability training in all areas of education. Within the computer graphics discipline itself, educators should ensure that students majoring in computer graphics demonstrate exceptional spatial skills. For non-computer graphics majors, CG educators can provide survey and discipline-specific courses that include training and practice in spatial ability applied to varied topics.

Knowing this opportunity exists, one may wonder what specific activities can be integrated into a course to help develop spatial skills. The following sections provide activities that computer graphics educators can use to development student spatial ability as well as references to studies that have evaluated their impact.

## 6. Improving Spatial Ability

To improve spatial ability through teaching and training one must acknowledge that there are two parts to instruction: the methods used and the deliverables or activities in which the student engages. Most of the spatial ability studies that have not found improvement have acknowledged the potential mismatch between method and activity – that is, either the method of instructional delivery or the activity performed was questioned. It is highly important that educators consider both method and deliverable when planning learning encounters for students. The methods used should match student learning styles (or, more appropriately, use several approaches to accommodate multiple learning styles), whereas activities should be applied to a specific context and require the use of spatial faculties. Concerning this later point, activities typically need to focus on development of one of the three

primary abilities (visualization, relations, or orientations) as appropriate for the content being taught.

### 6.1. Methods of Instruction

Procedurally there are three methods of instruction that can be used when students perform activities: learner only, learning groups, or mentor model. Each of these methods has positives and negatives associated with it.

In the learner only model—which is the most frequently used—the learner is given an activity and expected to accomplish the task independently and often outside of class time. While this is the most relied-upon technique, too often students do not have enough knowledge or experience in solving spatial problems on their own. Thus, they may not end up with the right answer or they may use inefficient strategies that yield the right answer, but accomplish the task in a round-about way. In any learner-only activity, the educator must ensure that the student has the requisite conceptual knowledge and has sufficient procedural knowledge to accomplish the task independently.

As a side note, often educators will provide students examples of solved problems and believe that they are enough of a starting point; "students should just be able to figure it out," is the mantra. However, just having problems and their solutions is not enough. Students need procedural knowledge or strategies that provide a structural mechanism for problem solving. Rovet states it best, "it may be inferred that there is little benefit of presenting problems and solutions if the means of solution is not indicated well (p. 171)." In all problems, but particularly spatial ones, students need a framework or strategy to help construct spatial conventions and to be able to utilize their spatial faculties. These strategies also reassure the student and build confidence.

The second most frequently used activity structure is the learning group scenario. In such activities, students are grouped (often at random or by self-selection) such that they collectively solve problems or accomplish some task. This type of activity is highly beneficial for certain members of groups—as any teacher can attest when you teach something to someone else, you often learn more than the one being taught. However, group activities can also be problematic when there are inactive members of the group or when it comes time to determine who did what. Groups are most effective when there is equal individual participation and when individual performance can be determined (and demonstrated) apart from group performance.

The last method of instruction is the mentor model. This method is often the best means to teach students problem solving relative to spatial ability. However, its use is actually somewhat rare. Such an activity may require the student to work simultaneously with an instructor in a software package, on a sketch, or on some other activity that the instructor and student complete concurrently. The benefits to such a method are that students are able to "see the way the instructor thinks" and develop mental methods for problem solving strategies and the like. The drawback to such a method (if overused) is that students may become dependent on the thinking of the instructor—they become

unable to detach themselves from reliance on the instructor and his or her methods.

When it comes to instruction educators need to consider intermixing these three different forms or methods. Too often educators (including this author) rely on only one form due to either convenience or feasibility. Nevertheless, intermixing these instructional forms should be considered.

## 6.2. Deliverables

While instructional method is indeed important, as important are the actual activities in which students engage. The spatial literature highlights several key areas that can be used to develop student spatial ability. However, many of the studies (and their approaches) are context-specific. The most important aspect of activities designed to improve spatial ability is that they be context specific. In biology, activities might be aimed at cellular construction or organic systems and relationships, requiring the students to exercise visualization or orientation abilities. In chemistry, activities might be aimed at molecular bonds or chemical interactions, using visualization and relations. Again, it is critical that spatial ability training activities be context specific so that the student is interacting with relevant content in a spatial way. Additionally, it is often helpful for the educator to acknowledge the spatial skills being used so that students become consciously aware of them (i.e., their own metacognition).

One might ask, “What about computer graphics? What are context specific examples of spatial ability training in this area?” The following three sections provide examples of three approaches used throughout the literature with suggested applications.

### 6.2.1 Sketching Activities

Sketching as a spatial ability training activity has broad application to art, science, and technology. Many researchers have used sketching (with all forms of instructional methods). For example, in computer science, sketching can be used as a procedural planning tool forcing students to visualize application flow, software inputs and outputs, as well as human-computer interfaces. Such activities exercise visualization abilities. In art, sketching can be used for composition planning. And, in engineering sketching can be used to exercise spatial ability by requiring students to fluidly transform orthographic drawings to pictorials or vice versa.

When one mentions “sketching” in computer graphics education, the word can conjure any number of things. Sketches can be artistic, transformational, structural, analytic, temporal, or for raw, real-time planning purposes. But in all of these cases, the sketch is designed to graphically, spatially, and often, temporally represent data that exists in some other form and/or to use the new representation for problem solving. Because of this quality, it is one of the best vehicles for exercising spatial ability. Several researchers acknowledge the impact of sketching on spatial ability [ABG02], [CD02], [CNC\*05], [MB05], [MCK93], [OLK03], [ORD96], [ROO94], [STR75].

### 6.2.2. Physical Activities

The use of physical models or the construction of physical models is another activity that can be used in computer graphics education to improve spatial ability. While the use of physical models is quite common in elementary and secondary education, it is less common in post-secondary education.

Often the use of physical visual aids can help connect the abstract to the concrete and assist students in creating spatial representations. For example, in engineering the use of “cut blocks” can be used to help students understand orthographic view construction, the intersection of primitives, developments, or cutting planes. In art and design the goal may be to “construct something” but physical approaches can also be used in other ways. For example, 2D shapes may be used to construct a layout or design. And, it is not uncommon in computer science to use Post-It notes or other paper-based elements (or even markers on a whiteboard) to plan out applications.

While in post-secondary education physical models are often chagrined—believing that student have grown past the “childish need” to handle and touch something to understanding it—the reality is that often students lacking in spatial ability can be helped by returning to this mode of experiencing objects to understand them [DEJ77], [MIL92], [NBT79], [PI71].

### 6.2.3. Computer Activities

A final approach to improving spatial ability is the utilization of the computer. Researchers have used numerous methods including application software (2D CAD, 3D CAD, animation, games, and virtual reality) as well as custom computer based training and other educational programs. Concerning the former, the biggest difficulty is getting the student to focus on exercising their spatial ability rather than controlling the software [MOH97]. For example, when a 3D environment is used, too often the student becomes engrossed on commands, interface items, and computer regalia, rather than using the tool to help visualize. Nevertheless, computer software and related tools provide a unique mechanism for developing spatial ability, as acknowledged by many researchers [AH03], [ALD95], [ATM97], [BER91], [BP93], [DEF\*94], [DIX97], [GAO92], [JOH91], [KIS90], [KK98], [LK82], [LM98], [MC87], [MC99], [MCC91], [MJ98], [MS94], [PBM\*85], [RA93], [ROS91], [SEX92], [SHA04], [SHU84], [SOR00], [STE01], [TB90], [TL97], [THO96], [YAG03], [ZAV87].

## 8. Summary

This contribution has provided an overview to the literature on spatial ability and provided a challenge to computer graphics educators to focus on spatial ability development within their courses. There is no doubt that spatial ability has an affect on many aspects of human performance and success. As well, while spatial ability is indeed partially biologically based, it can be improved

through specific training activities. It is the hope of this author that computer graphics educators will revisit their courses and integrate specific activities into courses for their majors and non-majors that are aimed at improving spatial ability.

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