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The Impact of Visualization Methodology on Spatial Problem Solutions Among High and Low Visual Achievers

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Abstract

As the result of a qualitative study, this contribution reports the major themes that emerged relative to student approaches and processes in spatial problem solving. Using phenomenological inquiry, differences between high and low spatial ability participants were examined. Pedagogically important findings included the behaviors of (1) working across views to solve problems, (2) double-checking while solving problems, and (3) the ability to decompose spatial problems. This article provides useful insights into how individuals with varying levels of spatial ability tackle engineering graphics problems. It also includes textural material from the study. The author makes a recommendation for the inclusion of spatial decomposition exercises in instructional materials.

Learning from Student Approaches to Spatial Problems

Although quantitative research typifies spatial ability literature, researchers such as Lohman and Kyllonen (1983) have indicated that qualitative research methodologies could add much to our understanding of spatial ability. As a result, this study used a phenomenological framework to examine spatial ability as experienced by engineering students (Mohler, 2006).

One of the emergent themes from the study was how students approached spatial problems and the processes they used. Findings from the study yielded important insights into the processes that high and low visualizers use while solving spatial problems, particularly pictorial creation problems. It also revealed the importance of decomposition skills in spatial problem solving. Primarily elicited through a talk-aloud approach as participants solved applied spatial problems, the findings were also supported through triangulation with other data sources.

What is Spatial Ability?

One of the aspects 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 (D'Oliveira, 2004; Eliot & Smith, 1984; Lohman, 1979).

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 (1928), El Koussy (1935), Thurstone (1938) and Thorndike (1921). Using factor analysis, subsequent researchers sought to define what composed spatial ability, without regard to how the ability developed or what processes were involved within it. Research by Slater (1940), Thurstone (1950), Guilford & Lacy (1947), French (1951), and others investigated this.

From the 1960s through the early 1990s, researchers began examining spatial ability in myriad ways. 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

(Cooper & Shepard, 1973; Kyllonen, 1984; Lohman, 1988; Pelligrino & Hunt, 1991; Shepard & Metzler, 1971). Other researchers examined spatial ability from a developmental perspective, looking at the development of spatial ability from childhood (Olson, 1975; Piaget & Inhelder, 1971). And, still others examined spatial ability from a strategy perspective (Kyllonen, Woltz, & Lohman, 1981; Lohman & Kyllonen, 1983) or differential perspective (Carroll, 1993; Harris, 1978; Lohman, 1984; Linn & Peterson, 1986; McGee, 1979; Maccoby & Jacklin, 1974; Nyborg, 1983; Voyer, Voyer, & Bryden, 1995). Interested readers may wish to review historical accounts that provide varying levels of detail regarding each of these (Carroll, 1993; Eliot & Smith, 1983; McGee, 1979; Smith, 1964).

Peering through the expansive literature one finds that the most generic and commonly accepted definition of spatial ability was provided by Lohman (1979) following a comprehensive reanalysis of the seminal research that preceded him. 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 (1979) stated 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 (relative to the problem), 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 reconfirmed Lohman's findings in this area and provided a unique viewpoint on intelligence and its composition (Carroll, 1993).

Strategy Research

Because this contribution focuses on different approaches to solving spatial problems it contributes to the expanding body of research in this area. Information-processing research has focused intently on problem solving strategies in spatial tasks (Carpenter & Just, 1986; Cooper, 1980; Cooper & Mumaw, 1985; Lohman, 1984; Mumaw & Pellegrino, 1984; Pellegrino, Alderton & Shute, 1984; Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990). This body of research indicates that there are differences between problem solving approaches in individuals; including the content and procedures of the steps, and the order of them (Carpenter & Just, 1986). These different approaches often lead to variance in problem solving efficiency and effectiveness (Lohman & Kyllonen, 1983). As well, the research indicates that individuals strong in spatial ability may have multiple strategies and that they may fluidly change strategies while solving problems (Cooper, 1980; Kyllonen, Lohman, & Woltz, 1984). The findings of this study contribute to this body of knowledge by looking for similarities and differences in the strategies and approaches used by high and low spatial ability students.

Overview of the Study

The purpose of this study was to elicit, describe, and analyze the experiences and perspectives of individuals with varying levels of spatial ability. Data sources included long interviews, talk-aloud tasks, focus groups, and researcher journal entries and observation notes. The sample was drawn from students enrolled in *CGT 163: Introduction to Graphics for Manufacturing* at Purdue University; a freshman engineering course that focuses on freehand sketching and computer-aided design to convey engineering ideas.

In the study, 12 students participated in in-depth interviews and eight students participated in one of two focus groups, totaling 20 participants in all (see table 1 on page 4). Phenomenological studies typically include three to 10 participants when the researcher is attempting to described experienced phenomena (Creswell, 1998; Dukes, 1984; Morse, 1994; Rieman, 1986). Sampling was based upon extreme case (Patton, 2002).

Students were identified as high or low in spatial ability based on Vandenberg Mental Rotations Test (MRT) score (Vandenberg & Kuse, 1978) and randomly assigned to an interview or focus group based on MRT score. Once assigned to an interview or focus group, the number of students in each was then balanced based upon gender, major, and semester. Interviewees and focus group participants were balanced across these variables to the extent possible. The MRT has been shown to be a valid (Zimowski & Wothke, 1986) and reliable (Vandenberg & Kuse, 1978) measure of spatial ability, and has been used by other researchers to determine high and low spatial ability (Miller, 1992; Zavotka, 1985).

Interviewees participated in three, 90-minute sessions. The first was aimed at eliciting experiences that the participant believed affected their spatial ability. The second interview required that participants solve three problems using a talk-aloud technique (Lodge, Tripp, & Harte, 2000; Nielson, Clemmensen, & Yssing, 2002). As shown in Figure 1(see page 4), one problem required that they sketch the multiviews of a pictorial, while the other problems required that they generate an isometric pictorial from given multiviews. The final interview was used as a summative activity, having the participant reflect on the development of their spatial ability during the semester, their learning in the course, and their participation in the study.

Talk-Aloud Tasks

A talk-aloud procedure was used during the second interview to elicit thoughts, feelings, approaches, and processes relative to spatial problem solving. However, it became apparent that more simplistic objects were needed because some participants could not complete the second problem at all. The researcher judged it highly likely that such participants would not be able to solve the third problem either because it was designed to be more difficult than problem 2. Rather than end the interviews prematurely, it seemed appropriate to present participants that could not solve problem 2 with a simpler problem. Three alternative problems were created that were actually parts extracted from the second problem. Figure 2 (see page 5) shows the three alternatives. The alternative problem given to the participant was based on where they started on the second problem. For example, if they started on the top of the object, alternative A was given. If they started on the front of the object, alternative B was given. Because of the complexity of the right-hand end, which included a compound angle, no participant started there; therefore alternative C was never used.

Observations from Student Problem Solving

Analysis of interview transcripts, observation notes, and participant solutions indicated behavioral differences between the HSP and LSP groups. Of importance were how the two groups worked across views, the frequency with which they double-checked themselves, and their ability to deconstruct spatial problems.

Working Across Views

High spatial ability participants (HSPs) had the tendency to work across views more frequently than low spatial ability participants (LSPs). When doing problem 1, this manifested itself in HSPs using the views they had already drawn to complete views on which they were currently working. In problems 2 and 3, it manifested in HSPs referring to the problem stimulus (and at times drawing directly on it) to compare the provided multiviews.

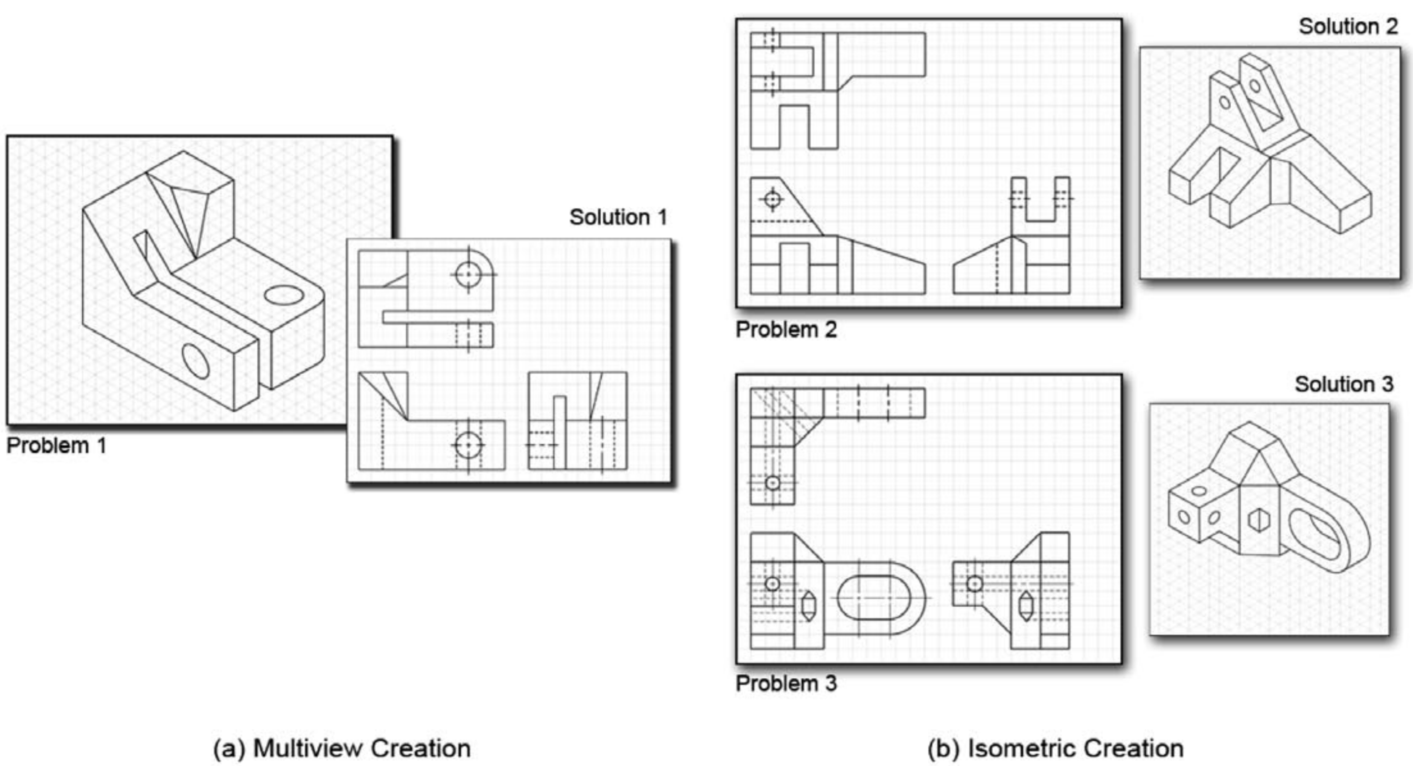
The researcher actually noticed the amount of looking across views in interview 2 with participant 04 (P04; the first of the second interview). His observation notes stated, "She is studying the drawing intently; doing a lot of looking across views." Observation data from other HSPs also acknowledged the frequency of this behavior. And when they were asked to reflect upon the talk-aloud tasks in interview 3, several HSPs mentioned doing this frequently.

Table 2 (see page 5) shows the data sources in which looking or working across views was evidenced as a characteristic common to HSPs. Low spatial ability participants (LSPs) are

Table 1. *Activities of the Participants*

Participants	Ability	Activity
1-6	High	3 in-depth, individual interviews
7-12	Low	3 in-depth, individual interviews
13-16	High	1 focus group
17-20	Low	1 focus group

Figure 1. ***Participants used a talk-aloud technique while solving (a) one multiview creation problem and (b) two isometric pictorial creation problems.***



not shown because it only appeared in the third interview with P12 when the researcher asked her directly about it.

P13, P14, P15, and P16 (focus group A) acknowledged that they also worked across views frequently helping to further confirm the importance of this behavior through triangulation. Table 3 (see page 6) provides various comments from the HSPs about looking across views as they were working and the importance of it.

In comparison, the LSPs did not appear to be working across views. For example, researcher observation notes for P10 as he was working on problem 1 acknowledged:

> *Does not appear to be looking across views very much. Is predominantly looking at the pictorial rather than checking front view on orthographic views. I noticed that earlier interviews students looked back and forth across views a lot.*

The researcher made a similar remark later in problem 2 when he wrote:

> *Participant is not looking at the orthographic views much. Is working on the double angle but not looking at orthographic views.*

Throughout the LSP interviews, the researcher repeatedly noticed and acknowledged that LSPs seldom appeared to be working across views. Additionally, none of these participants acknowledged the relevance or importance of this behavior when asked to reflect on the activity in interview 3.

Figure 2. ***The three alternatives were actually extracted parts of the original second problem. Alternative A is the top, alternative B is the front (or left end in the pictorial), and alternative C is the right-hand end of the object.***

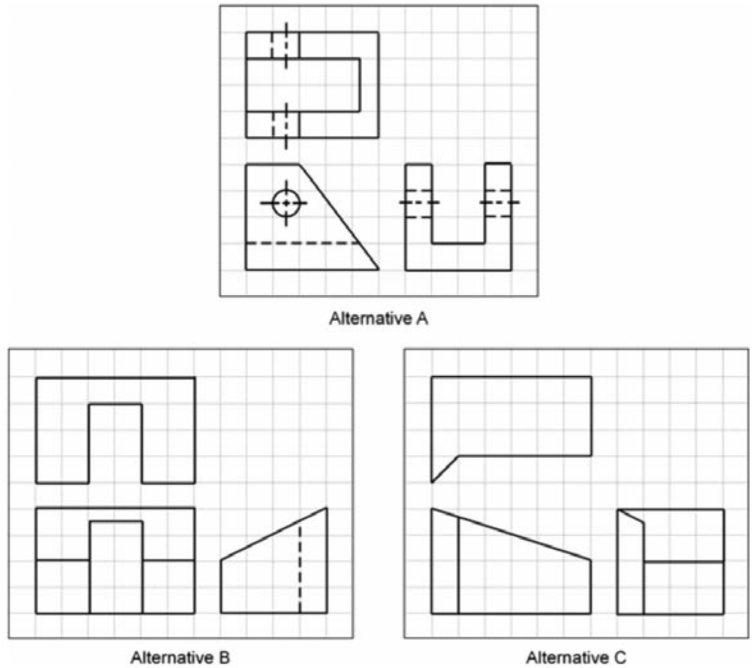


Table 2. Data Sources That Acknowledge Looking Across Views.

Participant	Interview 2 Transcript	Observation Notes	Interview 3 Transcript
P01	Y	Y	Y
P02	Y	N	Y
P03	Y	Y	Y
P04	N/A[1]	Y	N
P05	N	Y	Y
P06	Y	N	Y

[1]Interview 2 data was lost Because of recording error

Double-Checking Their Work

The second HSP characteristic that emerged was the frequency with which they double-checked themselves. This manifested itself in two different ways. The first was when a participant would complete a major portion of a drawing (e.g., a view in multiview or a feature in a pictorial). He or she would stop and check what had been completed. When drawing multiviews, the HSPs would often compare their solution view to the problem drawing, as well as compare their solution views to one another. When drawing a pictorial, the HSPs would compare the isometric version of the feature with the multiviews in the problem stimulus.

The second way this manifested was in real-time, as HSPs were drawing. The problems the participants completed required that they count blocks for measurement. HSPs would count blocks in the problem drawing, draw it out in their solution, and then recount the problem drawing again, and recount in their drawing to check it. P02 described it best when he said:

> *I always like to double, double-check. My dad always said when you were like working with lumber or anything, you always measure twice, cut once. It's kind of the same. I kind of try to use that same principle when I am doing this as well.*

Many of the HSPs acknowledged double-checking their work, often doing both types of checking several times for each problem. Again, while the LSPs were not void of checking themselves, they typically only checked themselves at the very end of the problem. It was not evident that they were consistently double-checking (in real time) throughout the problem like the HSPs were.

Decomposing Spatial Problems

Aside from their lack of working across views and infrequent double-checking, a common thread amongst the LSPs was their inability to decompose the pictorial drawing problems. Generally, all of the participants were able to do the multiviews in problem 1 independent of their spatial ability. While some forgot lines or features in one or more views, they all were able to solve the overall basis of the problem.

However, concerning the pictorial construction, the LSPs seemed to be unable to break the problem down, or decompose it, into simpler geometry in order to solve it. However, most of them, when given the alternatives, were able to solve the simplified alternatives. Table 4 shows the LSPs that were able to solve problem 2 or its component parts.

As shown in Table 4, P10 was the only LSP to solve problem 2 (and problem 3). Three other LSPs were able to solve one of the alternatives, and two of the LSPs could not solve any of them.

When an LSP could not solve problem 2 (and before giving them an alternative problem), the researcher asked if they could visualize the problem and describe it verbally. For example, he asked P09 if she could see the object in her mind or pieces of it, and she said she could not. He also asked P12 the same question. She said:

> *I can tell that...I am going to have two holes going through the top prong-looking things. And then this surface is back compared to this front surface. Hmmm, that line is hidden.*

Comments such as this led the researcher to conclude that P12 could indeed see at least the top part of the object, but from there, she did not know what to do. When the researcher gave her alternative A, she was able to draw it correctly.

Table 3. *HSP Comments about Looking or Working Across Views.*

Participant	About "looking across views..."
P01	I usually constantly look across the views.
P02	I just never really thought about things like that. When you're doing the sketch, you never dwell on if you're going from one to the other. I mean, you have to reference back and forth obviously... I guess you have to sort of look at all three in my mind. You have to be continuously relating to all three of them so you know what it looks like. I mean, there are three views. It's a three-dimensional object. If you just work off one...I think you might have some discrepancies and it might not look correct.
P03	Like if you get, if you can't do one view completely, you got two more views to go on. Half of the time, I can figure it out in some other view.
	Yeah, like if I'm ever confused, like they all line up, like perfectly, like even if you need to, like you could line up your top view and your right view. I mean, it's an extra sketch that's not needed, but you can do it in lightly, if you are actually having that much trouble.
P04	So I can see from these two views that there is a flat, single box with a line coming right about here.
P05	...you can only get so much from one view, that's why it's a multiview. So. you have to keep looking over at others to try to figure out piece by piece, "Ok this piece is going, based on this, this piece comes out based on this, this piece, you know looks like this," ...I mean I have, I can't focus on all of them at the same time. But you have to utilize the other two to understand one.
P06	Pick your base view and then from there build on the other parts of it. Because if you're trying to use 2 or 3 different views, as you know, as kind of the base view, you'll screw it up really easy. But if you kind of use one view as like your, this is set in stone, I'm going to think about everything from this one view, and then you build onto that view, and you build from this, you know, 2D and then into a 3D view, then it's a little it easier to construct it in your head, than it is to, just to try to take all three and throw them together.

Table 4. *LSPs Who Solved Problem 2 or Its Alternatives.*

	Did they solve...		
Participant	Problem 2	Alternative A	Alterative B
07	N	---	Y
08	N	---	N
09	N	---	Y
10	Y	---	---
11	N	N	N
12	N	Y	---

Given that three of the participants were able to solve portions of problem 2 (the alternatives, but not problem 2 itself), the researcher deduced that the LSPs did not seem to be able to break a problem down. Instead, they were either trying to visualize the entire object and could not, or would visualize a part of the object but not know what to do next. Several of the HSPs acknowledged that being able to break the problem down (spatially) for mental comparisons (such as the MRT) or visualization (on the sketching problems) was critical.

Reflections on MRT Task

To further support the rationale that LSPs could not decompose complex spatial problems, the researcher analyzed all participant comments relative to their approach in solving MRT problems. This was one of several reflective questions asked of all participants in interview 3.

Many of the participants, predominantly the HSPs, acknowledged using a part analysis approach to the MRT (i.e., a deconstruction approach). While they compared the stimulus object to the discrimination objects, they were looking for particular features in their object comparisons. In their mind, they had decomposed the object, looking for unique characteristics or object features. For example, P02 said:

> *I mean, I could look at it and I could almost instantly tell you, 'all right that's definitely not it and that ones not it' … just how when you would see like the blocks going one way and another way. I don't know, just like the feature of itself, like I could look at the next picture over and see that the bend was like opposite. It was like, you know, instead of going to the right, it was going to the left or something like that. That was primarily what I started looking for. I was really just starting to pick one end, I mean on there, when some of them would get kind of complex.*

In this segment, P02 acknowledged reducing the block configuration to a specific feature for comparison. P03 said it another way:

> *P03: Sometimes I would like try to rotate it with my hands, sometimes I would just draw a line in, I mean, my steps, really I didn't do more than a "which one matches or doesn't match" and cancel that out. Usually I could always find one simple point ...*
>
> *Researcher: A point on the object? You looked for pieces of the object?*
>
> *P03: Yeah, small things like that...*

HSP statements such as these led me to believe that they indeed had an ability to break spatial problems down. In the case of the MRT, they were able to find identifying features of the objects and use those to quickly discriminate which objects were the same object. LSPs did not indicate how they were solving the MRT, only that many of them found it difficult.

Participant Reflections

Data from interview 3 further solidified the realization that HSPs had the ability to decompose spatial problems. Throughout these interviews, several of the HSPs highlighted the importance of breaking a problem down, as did the course instructor (CI), who also participated in the activities.

For example, when working on problem 2, the CI said he would work on a "feature at a time" on the object. P01 used a similar description:

> *Um, I think I would like, take piece by piece...and then how all the ellipses and other pieces, try and connect by looking at the other views... I had to focus in on little pieces, and it didn't like, all come together, start like, coming together until I had most of it done.*

P01's statements, using words like "piece by piece," "connect," "little pieces," and "all come together," indicated that she was decomposing the objects mentally. P03 also admitted:

> *...what I do is I just kind of look at that [multiviews] and I can sort of, like, if I can't visualize the whole thing, sort of a process is like, I could probably visualize that like at an angle, cause like...I can see something like that in my head. And I can like start connecting the top view, start connecting the right side view, see what it's like in the front view and all that.*

P03 said he could not visualize the whole object, thus he decomposed it and mentally reconnected it. Similar to P02, he used the word "connecting" in his description. P05 stated:

> *Typically, cause this one [problem 2], I am having a little bit of a problem visualizing altogether. I can see pieces, like from this side one, I can see that this corresponds to this, um, and the holes … what I am going to start by doing is sketching the very front and sketching everything that is on the very front of the object, which is just going to be this [she will draw one piece of the object].*

Statements such as these provided further qualitative evidence that something was enabling HSPs to dissect the spatial problems and work with them in a piecemeal fashion. P06 provided probably the best description of problem decomposition. He recommended:

> *I would say always try to break it up. I think the main problem, if you're trying to go from multiviews to 3D views is you're trying to look at the entire piece all at once. And so, I know I do that and you kind of like, I screw stuff up because when you're looking at everything, it kind of, it's easy to get real messed up. But if you break it apart into easier sections, and easier blocks, and you know, break it up three, four, [or] five different parts then you can, it's easier to visualize each of the parts and then it's easier to put them altogether and it's easier to just kind of think of the entire thing in one piece.*

As the researcher pondered the talk-aloud and interview 3 transcripts, it was evident that the HSPs had broken down the problems just as P06 had described. The researcher's observation notes attested to the reoccurring theme focused on problem decomposition. For example:

- For P01 the researcher wrote, "Decomposing features?"
- For P03 he wrote, "Using CSG [constructive solid geometry] approach to construct the top U-shape."
- For P04 the researcher wrote, "Decomposing object into processible [sic] chunks"; "Approaching it feature by feature."

By examining HSP processes and approaches to the MRT test, the pictorial problems in interview 2, as well as his observation notes, it was evident that HSPs were using mental decomposition or deconstruction techniques in their problem solving, whereas LSPs were not. And, because LSPs were able to solve some of the pictorial problems (when given the alternatives) it became evident that they needed instruction on deconstructing problems mentally.

Summary and Conclusions

This contribution has provided expository on the major behavioral differences that emerged relative to student approaches and processes in spatial problem solving. As discussed, contrast between high and low spatial ability participants revealed differences in how much the participants worked across views (and the importance they placed on this activity), the degree to which they double-checked themselves (frequency and throughout the problem solving process), and their ability to decompose spatial problems (their ability to simplify and breakdown spatial problems into cognitively manageable chunks).

While this study cannot provide the "why" to these findings, it does reveal unique characteristics and differences that were found when observing high and low spatial ability participants. While further research is needed to probe and potentially answer "why" these characteristics were observed, the findings have implications for how students are taught and the activities they engage in to improve their spatial ability.

It seems apparent to this author that time should be devoted to problem decomposition; teaching students how to strategically dissect spatial problems. It is likely that instruction in both 2D and 3D object decomposition would be beneficial. However, future studies should investigate the efficacy of each of these.

While information processing researchers have placed emphasis on understanding the cognitive processes involved in spatial cognition–that is, what occurs in the mind and when–it appears that little attention has been focused on developing instructional methods that help students decompose and structure problems. Research that has tried various direct and indirect instructional methods also lacks a focus on decomposition. Based on the findings of this research, decomposition appears to be highly important, even though little attention has been given it. Instructional activities along these lines should be developed, tested, and assessed.

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