# Computerized Representations of 3D Structure: How Spatial Comprehension and Patterns of Interactivity Differ Among Learners

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## Abstract

A number of educational fields are introducing computer visualizations into their curricula, yet our understanding of the cognitive phenomena underlying learning from these materials is relatively limited. We examined how learners used an interactive 3D computer visualization to comprehend spatial relations in a virtual anatomy-like structure. Our goal was to examine the relationships between a number of variables, including individual differences among learners (such as spatial abilities), and features of the computer visualization (such as the nature of the interface). We present two experiments in which we investigated spatial comprehension and patterns of interactions among individuals.

## Introduction

In recent years, computer visualizations have become increasingly prevalent throughout education. New advances in computer graphics have made it possible to produce powerful visualizations, and there is currently much excitement about the potential of these resources among educators. Across many curricula, computer-supported interactive visualizations are being hailed as an important new development, capable of fundamentally changing the way learners interact with information.

One discipline that has enthusiastically embraced the educational potential of computer visualizations is medicine. The study of anatomical structure and function is a fundamental aspect of medical training, and technology has long been employed to enhance anatomy teaching, in the form of diagrams, bench-top models, and cadaver dissection laboratories. Compared with today's technologies, however, these traditional learning materials have a number of limitations. Diagrams are unavoidably restricted to two dimensions, generally entail only cardinal views, and bear little resemblance to real anatomy, while bench-top models are often useable only once as they are of little value once they have been "dissected". Cadavers, although the most naturalistic of these materials, are rare commodities, whose use in medical schools is becoming increasingly restricted due to the expense of maintaining dissection laboratories.

Many medical educators view 3-D computer visualizations as a viable alternative to these traditional learning resources. Unlike traditional materials, computer visualizations are flexible, permitting the alteration of parameters such as anatomical variability, disease-state or viewpoint-perspective, and can be easily re-used with little cost. They can also be widely disseminated, affording access outside the traditional constraints of the classroom. As a result, medical education has recently begun a dramatic shift towards introducing digital representations into its learning programs. While recognizing that not all aspects of medical education can be accomplished through computers, the Association of American Medical Colleges (AAMC) particularly recommends digital representations for the study of anatomical structure and function "Priorities include sophisticated simulations, clinical cases, 2-D and 3-D images and other kinds of 'core' resources that can be incorporated into individualized learning programs" (Florance, 2002, p. 15).

However, despite much optimism about the educational potential of 3-D computer visualizations, our understanding of how learners interact with these representations is relatively limited. While cognitive scientists have made important contributions to research on external visualizations, the work to date has concentrated primarily on static 2-D representations such as diagrams and graphs. Recent research has begun to address questions such as how these 2-D representations are used in higher-level cognitive tasks (e.g., Larkin & Simon, 1987; Pinker, 1990), how and why they work (Larkin & Simon, 1987; Koedinger & Anderson, 1990), how we draw inferences from them (Pinker, 1990; Carpenter & Shah, 1998; Kosslyn, 1990; Hegarty, 1992), and the principles that make them more or less effective (Kosslyn, 1990). We know relatively little, however, about how learners interact with dynamic 3-D computer visualizations, i.e., representations that are not only animated but that represent space in three dimensions.

One factor that may be key to acquiring anatomical knowledge from such representations is *spatial ability*. This term refers to cognitive functions concerned with representing and processing spatial information. Research suggests that there are several somewhat dissociable spatial abilities that vary significantly within the general population, and these have been comprehensively documented through standardized testing (for a review, see Carroll, 1993; Eliot & Macfarlane-Smith, 1983; Lohman, 1988). The most robust and well documented spatial ability, *spatial visualization*, is involved in tasks that entail "apprehending, encoding, and mentally manipulating spatial forms" (Carroll, 1993, p. 309). It is possible that these types of processes are involved in understanding interactive 3-D computer visualizations.

While computer visualizations are often seen as having the potential to enhance or support cognition, it is not known whether these hypothesized benefits are equal for all learners, or whether they differ for individuals with varying levels of spatial ability. For example, interactive computer visualizations might "augment" cognition equally for high-spatial and low-spatial individuals, or they might act as a type of "prosthetic" for those with poor internal visualization ability, so that interacting with them improves the performance of low-spatial learners more than that of high-spatial learners. Alternatively, however, it is possible that some minimum level of spatial ability is a necessary prerequisite for learning from these types of representations, in which case they would have a greater facilitating effect on the performance of high-spatials than low-spatials, magnifying the differences between them.

Although spatial abilities have long been known to predict anatomy learning through traditional methods (Just, 1979; Rochford, 1985), more recently they have been shown to affect anatomy learning from 3-D computer visualizations (Garg et al., 1999; 2001). In a study where multiple views of 3-D anatomy were presented to medical students via a rotating computer visualization, a subsequent test of anatomical knowledge showed a significant disadvantage to individuals with poor spatial abilities (Garg et al., 1999). For these students, learning was effective only if the display was restricted to a simple depiction entailing just two cardinal views. Such findings suggest that complex 3-D computer visualizations might actually impair spatial understanding for low-spatial individuals.

The effects of spatial ability, however, may be moderated by the characteristics of the computer simulation. The performance of low-spatial medical students has been enhanced, for example, by allowing them to direct the rotation of the visualization, suggesting that learner control contributes significantly to the successful integration of complex spatial information (Garg et al., 2001). Other features that might potentially enhance or diminish understanding include variables such as the complexity of the image, the depth cues available, and the type of interface used to manipulate the visualization. In order to guide the future evolution of anatomical visualizations, these factors need to be explored, and the optimum combination of features established.

Another potentially important factor is the learner's proficiency for manipulating the computer simulation. One explanation for the discrepancy between high and low spatial learners is that low-spatial individuals may be less adept at exploiting the interactive capabilities of 3-D visualizations. It is possible, however, that such differences are essentially a matter of strategy, in which case it may be possible to distill the key characteristics and teach successful strategies to low-spatial learners. Observing individuals interacting with computer visualizations may provide us with insights into the factors that contribute to effective understanding, which could then be integrated into a training program to enhance these abilities.

The purpose of this research was to examine how learners interact with a 3D computer visualization while attempting a task in which they had to comprehend the spatial relations in a virtual structure. We asked participants to imagine two-dimensional cross-sections or "slices" of a virtual 3-D structure (see Figures 1 & 2). In order to complete the task, participants had to formulate a mental model of the computer visualization, encompassing both external and internal structure, to allow them to imagine what the cross section would look like. In two experiments we investigated the roles of interactivity and spatial ability in the comprehension of 3D computer visualizations, and compared the effects of different interface technologies. We predicted that both interactivity and spatial ability would be related to performance on this task. We also examined the patterns of interactions made by learners, and explored how they related to individual differences in spatial ability and performance on the task.

## Experiment 1

### General Method

Sixty undergraduates were presented with a fictitious anatomy-like structure (to avoid prior knowledge confounds) in the form of both printed 2D images and a 3D computer visualization that could be rotated in *x*, *y* and *z* dimensions. A superimposed vertical or horizontal line on the printed image indicated where they should imagine the structure had been sliced. The task was to draw the cross-section at that point, as if seen from a viewing perspective specified by an arrow. The drawings were assessed for spatial understanding using a standardized scoring scheme. Participants were randomly allocated to one of two conditions. The *active* group was allowed to rotate the computer visualization at will during the drawing task. The *passive* group had no control over the movements. Using a yoked pairs design, the manipulations performed by the active participants were recorded and later played back to the passive participants, so that both members of each pair received exactly the same visual information.

In both experiments, spatial visualization ability was measured via the Mental Rotation Test (Vandenberg &

Kuse, 1978) and a modified version of Guay's Visualization of Views test (Eliot & Smith, 1983).

In Experiment 1, the control interface was a simple key-press system. Participants hit a key to select an axis (*x*, *y* or *z*), and then used two keys to scroll forward and backward within that axis. The key presses produced rotations of the virtual object in real time.

**Scoring.** The drawings were scored on 4 standardized criteria: 1) Number of ducts: Does the cross-section contain the correct number of ducts? 2) Outside shape: Is the outer shape of the slice correct? 3) Duct relations: Are the spatial relations among ducts correct to +/- 20 degrees? 4) Duct position: Are the ducts placed in the correct region of the slice? (Criterion 3 was applied only to cross-sections containing more than one duct.)

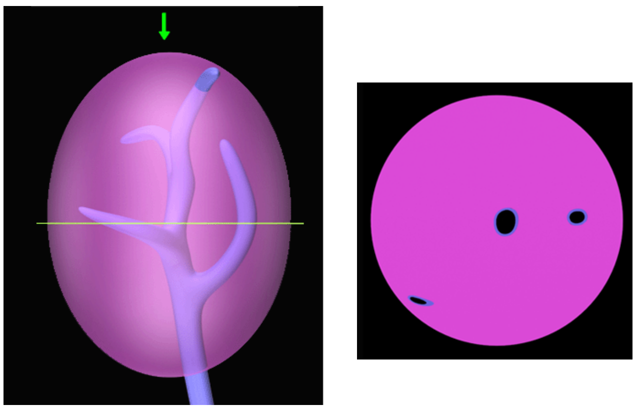

Figure 1: Left: Fictitious anatomy-like structure (computerized version did not show the cutting plane or viewing-direction arrow). Right: correct cross-

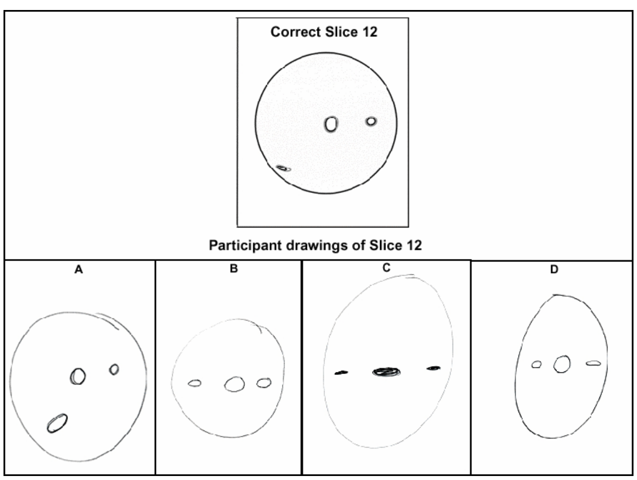


Figure 2: Sample drawings by participants (below), and the correct cross-section (above).

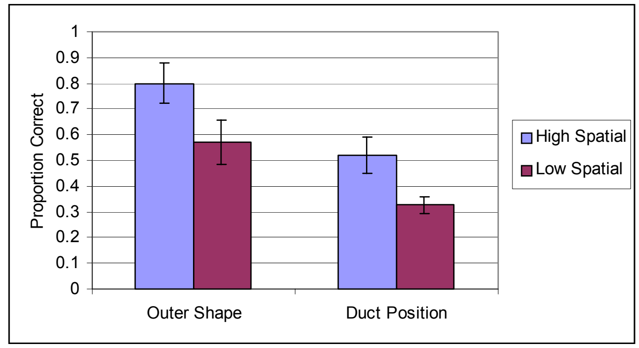


Figure 4: Mean performance on two key performance indicators, by spatial ability

## Results

**Performance on the Drawing Task.** An aggregate measure of spatial ability was computed (mean of *z*-scores from the MRT and Guay tests). Where the analysis required the division of participants into high and low spatial ability groups, a global median split was calculated from both experiments, to make the conclusions comparable across the two studies. Participants who scored above and below this criterion were categorized as high and low spatial ability, respectively.

An analysis of correlations among the four performance measures indicated two separable factors: 1) outer shape and 2) duct location (aggregate of duct relations and duct position measures, which correlated highly; $r$ = .79). Number of ducts was not included in the analyses because its relationship to the other measures was ambiguous.

There was no significant difference between active and passive conditions on any of the four performance measures (see Figure 3).

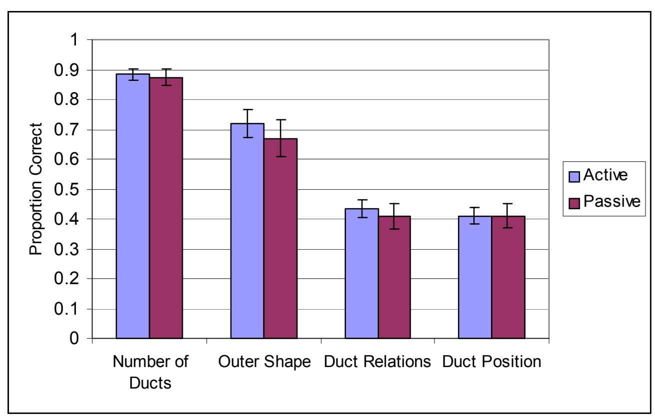


Figure 3: Mean performance of active and passive groups in Experiment 2, on the four standardized scoring criteria.

A correlation analysis found a significant positive correlation between spatial ability and performance on the duct location measure. The correlation was somewhat stronger under passive viewing ($r$ = .50, $p$ = .005) than under active control ($r$ = .39, $p$ = .03). There was no significant correlation between spatial ability and performance on the outer shape measure.

An independent samples t-test showed a significant difference between high- and low-spatial participants in the passive condition on the aggregate duct location measure ($t$ = 2.66, $p$ = .01; see Figure 4). This difference was not significant in the active condition. The outer shape criterion showed the same trend, but the difference under passive viewing was only marginally significant ($p$ = .07).

**Patterns of Interactivity.** Analysis of the movements made by the active participants was performed using the MATLAB programming toolkit. Interactivity data files were structured with time-stamps of *x, y,* and *z* position data for the anatomical stimulus seen in Figure 1. In order to analyze the views that participants observed, we generated plots like the one shown in Figure 5. The plots showed very little consistency among participants, with no clear preferred movement strategies or patterns of interactivity emerging for any given slice.

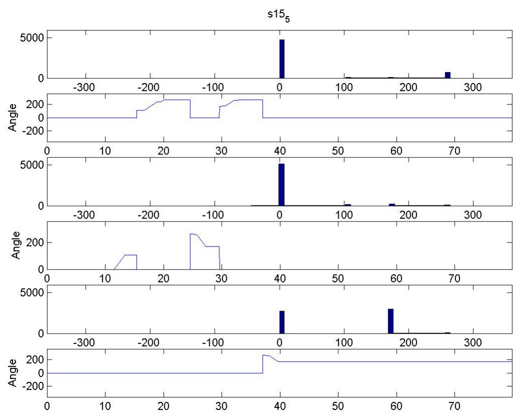


Figure 5: Interactivity data from one participant in Experiment 1. The plots are arranged vertically in pairs. The top, middle, and bottom pairs show movements in x, y, and z coordinates, respectively. The upper plot in each pair has *angle* on the x-axis, and indicates number of time-bins spent at each location. The lower plot in each pair has *time* on the x-axis, and indicates changes in angle over time.

To gauge frequency of use, we analyzed whether a participant moved the stimulus from the origin on any given trial. Patterns of interactivity differed somewhat between low and high spatial participants. On average, participants with low spatial ability interacted with the stimulus more often (93% of all trials, compared with 81% of all trials for high spatial participants).

## Discussion

The results of Experiment 1 showed no advantage to performance on this task from active control. Spatial ability proved to be a much stronger predictor of performance than active control versus passive viewing. This was especially true for the duct position measure, suggesting that this function required participants to use some form of visualization process, and/or to understand the spatial relations within the structure. By contrast, the outer shape measure did not correlate with spatial ability, suggesting that this feature could be identified using a non-spatial process, such as the application of a propositional rule (e.g., “this is an egg-shaped object, therefore horizontal slices are circular and vertical slices are oval”).

Participants with low spatial ability interacted with the stimulus more often than those with high spatial ability. One possible explanation for this finding is that people with high spatial ability are less reliant on the external visualization because they have enough information from the static view, and/or from their internal representation of the structure. However, this account is speculative, and requires further exploration. In any case, the absolute difference in frequency of use between high and low spatial participants was not very large.

Across all participants, there were no consistent patterns of interactivity. This lack of conformity in the types of manipulations used suggests little agreement among participants as to how to use the interactivity in an optimal way. It is possible that this is at least partly due to the nature of the key-press interface, which was not particularly intuitive or naturalistic.

A possible explanation for why we found no advantage of active control may also lie in the nature of the interface. The key-press control system used in Experiment 1 was not intuitive, and as such it is possible that merely operating it produced a significant additional cognitive demand on active participants, counteracting any potential benefits from active control. If this is the case, then an interface that produces a smaller cognitive load might allow the real advantage from active control to emerge. The purpose of Experiment 2 was to test this hypothesis.

# Experiment 2

## Method

Experiment 2 followed the same general method as Experiment 1, but participants used a different mechanism to control the rotations of the virtual object. The interface was a more intuitive hand-held device, comprising a 3 degrees-of-freedom motion sensor (the *InterSense Intertiacube2*) mounted inside an egg-shaped casing. This translated the rotational movements made by the participants in real time to the object on-screen. All other aspects of the experimental design and scoring system were identical to Experiment 1.

## Results

**Performance on the Drawing Task.** The drawings were scored on the same four standardized criteria as in

Experiment 1, and the same global median split was used to differentiate high- and low-spatial participants.

As in Experiment 1, there was no significant difference between active and passive conditions on any of the four performance measures (see Figure 6).

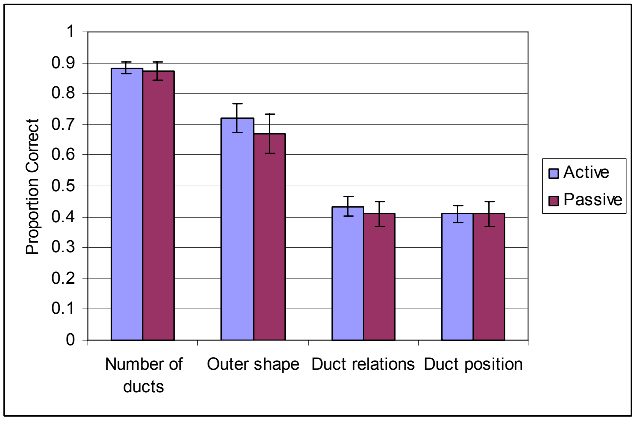


Figure 6: Mean performance of active and passive groups in Experiment 2, on the four standardized scoring criteria.

In contrast to Experiment 1, the correlation between spatial ability and the duct location measure was only marginally significant under passive viewing ($r$ = .35, $p$ = .05), and it failed to reach significance under active control ($r$ = .34, $p$ = .06). Consistent with this lack of correlation (and in contrast to Experiment 1), there was no significant difference between high- and low-spatial participants on the duct location measure under passive viewing. Once again, there was no significant correlation between spatial ability and performance on the outer shape measure.

**Patterns of Interactivity.** The patterns of interactivity observed in Experiment 2 differed substantially from those found in Experiment 1. Overall, the interactivity was used more frequently in Experiment 2. In addition, whereas in Experiment 1 the percentage of interaction across all trials differed according to spatial ability, all participants in Experiment 2 interacted with the stimulus to a similar degree.

An inspection of the interactivity plots from all participants revealed consistent patterns of interactions. Participants used the interactive functions in highly similar ways on any given trial. A detailed analysis indicated that participants spent significant amounts of time focusing on specific views of the structure. The favored views correspond to optimal key views for solving each trial. For example, Figure 7 shows the "optimal" view for Trial 5, and one participant's interactivity plot illustrating significant time spent on this view.

### Discussion

Experiment 2 applied the same general method as experiment 1, but a different control mechanism was used. The interface was a more intuitive hand-held device, which translated the rotational movements made by the participants in real time to the object on-screen. All other aspects of the experimental design and scoring system were identical to Experiment 1.

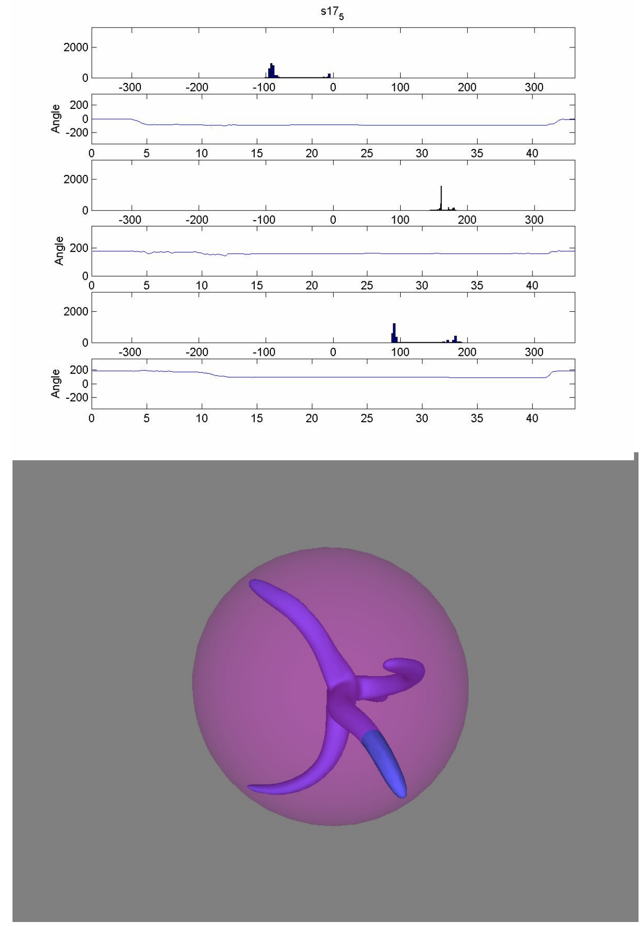


Figure 7: Above: Interactivity data from one participant in Experiment 2 (see Figure 5 for an explanation). Below: The view of the structure on which the majority of time was spent.

Once again, no advantage on task performance was found for active control compared to passive viewing, even with the more intuitive and naturalistic interface. Compared to Experiment 1, however, the effect of spatial ability on performance was substantially attenuated.

The patterns of interactivity showed much greater consistency across participants than in Experiment 1. This finding provides indirect evidence for our assertion that the interface was more intuitive or naturalistic, as all participants used it in similar ways, even though they received minimal training in its operation.

## General Discussion

Experiments 1 and 2 used the same general method, but a different interface for controlling the movements of the stimulus. In Experiment 1, participants used key presses to rotate the structure, whereas in Experiment 2 the interface was a more intuitive hand-held device, providing a more naturalistic form of control.

Neither experiment found evidence for an advantage of active control over passive viewing. This finding contrasts with previous studies from our lab, which showed that participants did better when they were allowed to actively manipulate the structure, compared to when they simply watched a rotating version of the structure. How can we account for this discrepancy?

A key difference between the earlier study and the two reported here is that in the present experiments, active and passive participants saw the same visual information. The fact that they did not differ in performance suggests that it is access to informative views of the structure, rather than interactivity *per se*, that is critical for performance on this task. Thus, when both participants see the same information, they do equally well, even if they do not directly control the movements of the object. Future studies will explore this "informative views" hypothesis.

As in previous studies, we found that spatial ability was important for performance, but in Experiment 2 the correlation with spatial ability was substantially attenuated relative to Experiment 1. It seems likely that this difference was due to the interface, but at present we do not have a coherent account of the mechanisms responsible.

Perhaps the most interesting result for the purposes of this symposium is the differences we observed in the patterns of interactivity in the two studies. It appears that the nature of the interface caused participants to interact with the stimulus in qualitatively different ways. In Experiment 2 we found much greater consistency among participants, and less of a difference associated with spatial ability than in Experiment 1. It is interesting to note that in Experiment 2, high and low spatial participants also differed less in terms of task performance compared to Experiment 1, although it is too early to say whether there is a causal relationship between these two observations.

We are presently continuing our analysis of the interactivity data from these studies. We seek to address the following questions:

1) What patterns of interactivity characterize learners with good and poor spatial visualization abilities?
2) How do different patterns of interactivity relate to performance on the cross-section task?
3) What is the nature of this relationship? i.e., is task performance influenced by spatial ability alone, by interactivity alone, or by a combination of both factors, with or without one mediating the other?
4) What effect does the nature of the interface have on the interactions observed?
5) What are the implications of these conclusions for the design and implementation of these types of representations in educational contexts?

Taking these issues as a starting point, we will discuss possible conclusions arising from the data patterns.

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