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Getting a Handle on Learning Anatomy With Interactive Three-Dimensional Graphics

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In 2 experiments, participants learned bone anatomy by using a handheld controller to rotate an on-screen 3-dimensional bone model. The on-screen bone either included orientation references, which consisted of visible lines marking its axes (orientation reference condition), or did not include such references (no–orientation reference condition). The learning task involved rotating the on-screen bone to match target orientations. Learning outcomes were assessed by asking participants to identify anatomical features from different orientations. On the learning task, the orientation reference group performed more accurately, directly, and quickly than did the control group, and high-spatial-ability individuals outperformed low-spatial-ability individuals. Assessments of anatomy learning indicated that under more challenging conditions, orientation references elevated learning by low-spatial-ability individuals to a level near that of high-spatial-ability individuals. The authors propose that orientation references assist this learning process by defining the object's main axes or providing distinguishable features.

Keywords: anatomy learning, individual differences, manual rotation, spatial cognition, virtual reality

There is a growing trend to use virtual learning resources, such as interactive three-dimensional (3-D) graphics, to augment and even replace real-world experiences in classrooms and workplaces, for example, in training of medical personnel, engineers, mechanics, skilled tradespersons, and assembly-line workers. Reducing expenses, reaching a wider audience, eliminating dangerous conditions, and coping with limited resources are often cited as justification (Bearman, 2003; Hallgren, Parkhurst, Monson, & Crewe, 2002; Reznick & MacRae, 2008). Notably, computer models and virtual experiences have been replacing cadaver and other tangible materials in the modern medical classroom (Brenton et al., 2007; Ieronutti & Chittaro, 2007; John, 2007; Nicholson, Chalk, Funnell, & Daniel, 2006; Reznick & MacRae, 2008). Occasionally stated but often assumed is the idea that virtual learning resources are as good as, or even better than, their real-world counterparts, although supporting evidence is sparse (Arnold & Farrell, 2002; Reznick & MacRae, 2008).

Despite their obvious advantages, there is some evidence that interactive 3-D graphics are difficult to use, especially for individuals with low spatial ability (Cohen & Hegarty, 2007; Keehner, Hegarty, Cohen, Khooshabeh, & Montello, 2008). For example, spatial ability is related to learning of complex and spatially demanding skills, such as surgical procedures, with virtual resources (Hegarty, Keehner, Cohen, Montello, & Lippa, 2007). Similarly, spatial ability is related to success in learning from 3-D virtual resources, such as when learning anatomy (Garg, Norman, Spero, & Maheshwari, 1999; Levinson, Weaver, Garside, McGinn, & Norman, 2007; Luursema, Verwey, Kommers, Geelkerken, & Vos, 2006).

In this set of experiments, we investigate the hypothesis that providing orientation references—visible lines marking the main axes of an object—will improve people's performance when manually rotating a virtual object (e.g., an on-screen representation of a bone) and when encoding the structure of that object. Examples of an object with and without orientation references are shown in Figure 1. We suggest that orientation references provide the learner with a *cognitive handle* that enables them to better manipulate virtual objects. We suggest that if learners are able to more efficiently manually rotate the virtual object, this frees up mental resources for developing a mental representation of the virtual object. The goals of this project were to investigate whether orientation references are helpful when manually rotating virtual objects and whether orientation references help learners develop better mental representations during anatomy learning. Because spatial ability has been shown to be related to performance in learning anatomy (Levinson et al., 2007; Rochford, 1985), we also evaluated the role of spatial ability. In particular, we were interested in whether orientation references helped low-spatial-ability learners. This research makes a theoretical contribution to our understanding of learning of complex objects and an applied contribution through improvements in the design and delivery of virtual learning resources.

To investigate learning using virtual objects, we studied a learning task in which students learned both the features of a complex, 3-D anatomical object, as illustrated in Figure 2, and the spatial

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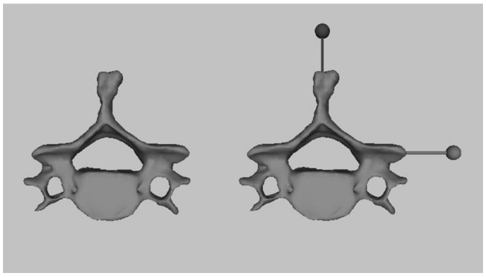


Figure 1. The model on the left shows the control condition bone. The model on the right shows the bone in the orientation reference condition, i.e., with vertical and horizontal poles. Both models are shown in a canonical orientation, the orientation used as the start position for all trials.

relations between these features. We studied this type of learning in the context of anatomy education because it represents an area where virtual learning resources are increasing in popularity. Both visual knowledge (feature identification) and spatial knowledge (spatial relationships between features) are required to form a useful mental representation of a complex anatomical object. In the learning task (manual-rotation trials), participants had to manually rotate a 3-D virtual model of a bone (a human vertebra) using a handheld interface to match a specific target orientation (as illustrated in Figure 3) and note the appearance and location of a target feature. In the course of rotating the virtual bone, we expected students to gain visual knowledge of the bone's features and spatial knowledge of the relationships between features by physically moving the virtual bone between targeted orientations. We measured knowledge after the learning trials by testing participants' ability to identify features from practiced and unpracticed orientations of the bone. We also measured how efficiently participants manipulated the virtual object during the learning trials.

The virtual lesson was intended to simulate a common teaching practice used in many anatomy classes from high school through medical school, that is, learning by exploration and manipulation of anatomical objects. This is an important area of research because technological innovations are a driving force behind many new teaching practices in medical education. Our study sought to evaluate a common learning scenario that simulated a learner working with a textbook illustration and a supplemental virtual object. Such a scenario creates a situation where students are challenged to develop a useful internal representation of some part of the anatomy from a static, two-dimensional (2-D) image. Traditionally, cadaver dissections and patient work help medical students develop anatomical knowledge, but these practices also carry disadvantages. Virtual materials, explored in this study, allow students to view objects from the more common noncanonical orientations that are not typical of textbook illustrations or anatomical atlases and offer a reasonable means of providing students with important learning experiences prior to their practical work with cadavers and patients.

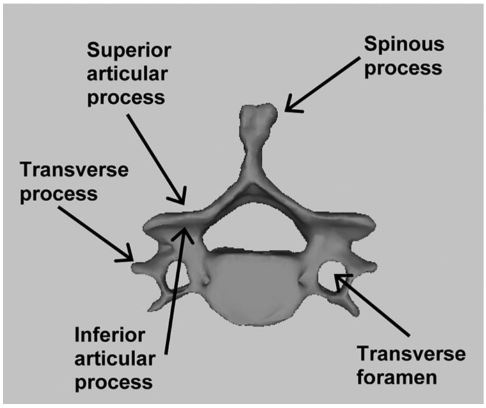


Figure 2. A model of the human cervical vertebra oriented in the starting position, indicating the five anatomical structures to be learned.

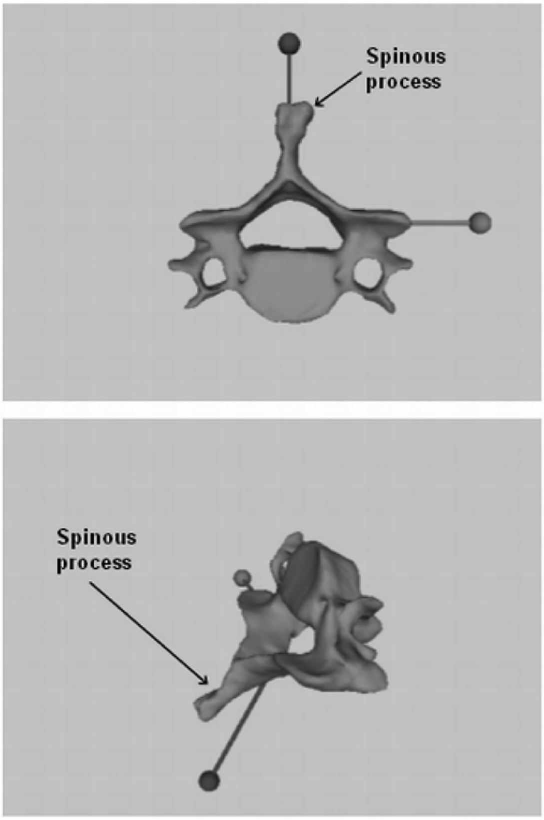


Figure 3. An example target orientation for the orientation reference condition. The top part of the page always showed the bone model in the starting orientation. The bottom part of the page always showed the bone model in the target orientation. One of the five anatomical structures (in this case, the spinous process) was indicated on each orientation of the bone in each trail.

Is Spatial Ability a Predictor of Performance of Medical Skills?

Previous research suggests that an individual's level of achievement in several medical professions, including surgery, dentistry, and nursing, is related to their spatial ability (Anastakis, Hamstra, & Matsumoto, 2000; Cuschieri, 1995; Gibbons, Baker, & Skinner, 1986; Grace, 1989; Hegarty, Keehner, Khooshabeh, & Montello, 2009; Keehner et al., 2004). Although both high- and low-spatial-ability individuals can acquire spatially demanding medical skills with practice (Wanzel, Hamstra, Anastakis, Matsumoto, & Cusimano, 2002), spatial ability continues to predict performance after many learning sessions (Keehner, Lippa, Montello, Tendick, & Hegarty, 2006).

All medical fields rely on foundational knowledge in anatomy, which is spatially demanding in that it involves knowledge of the 3-D features and the location of anatomical structures and spatial relations between these features. Thus, it is not surprising that spatial ability has been found to be correlated with anatomy learning (Rochford, 1985). Furthermore, in medical practice, professionals are called upon to recognize and interact with anatomical structures from many different orientations, not just the canonical orientations viewed in textbooks. Virtual models of anatomy (e.g., presented via computer displays) have been advocated as a low-cost way of training anatomy that enables professionals to learn to recognize anatomical structures from different orientations. During training, students can interact with these models to view the anatomy from different orientations.

Basic research on object recognition supports the use of virtual models showing that actively controlling a virtual 3-D object during learning (as compared with passive viewing of the object) leads to more efficient recognition of the object after practice (Harman, Humphrey, & Goodale, 1999; James, Humphrey, & Goodale, 2001). However, research that used these methods to teach anatomy found that low-spatial-ability individuals had particular difficulty manipulating 3-D virtual anatomical models and had poorer learning of anatomy compared with high-spatial-ability individuals (Garg, Norman, Eva, Spero, & Sharan, 2002; Garg, Norman, & Spero, 2001; Garg, Norman, Spero, & Maheshwari, 1999). Further, Garg et al. investigated the value of learning by interacting with multiple views versus canonical views of a learned object. They concluded that there was no advantage to multiple views over canonical views and that control was not useful if canonical views were provided to the learner. However, these investigations did not consider the situation where learners need to develop spatial associations between features that are not readily visible from canonical views, a condition common in anatomy learning. We suggest that when the goal is to develop structural knowledge of a complex 3-D object, it is unlikely that one or even a few views will support the development of a coherent mental representation, without active control. We propose that when a complex task, such as medical training, requires that multiple spatially related pieces of information be derived from an object, active control is useful and, further, spatial ability is an important predictor of success.

Do Virtual Learning Resources Require Spatial Ability?

Theoretically, there are several reasons to expect that a curriculum that uses virtual learning resources will cause problems for students with lower spatial ability. Manual rotation of an object, including a virtual object, in a goal-directed task is spatially demanding because it is guided by the mental rotation of that object (Ruddle & Jones, 2001; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger, 2001; Wohlschläger & Wohlschläger, 1998). With the goal of moving an object to a desired orientation, mental rotation is used both in planning the movement and in comparing the real object with its mental representation as it is moved. Given the suggested employment of mental rotation in manipulating virtual objects, and given that low-spatial-ability individuals have difficulty with mental rotation (Hegarty & Waller, 2005), individuals with lower spatial ability are likely to be less efficient and less accurate in manually rotating virtual models of anatomy during learning.

Virtual objects burden lower spatial ability students with the need to form 3-D mental representations from 2-D representations on a computer screen. This burden is compounded by the impoverished visual and sensorimotor cues provided by virtual objects and the interface used for viewing and rotating the object (Chui et al., 2006). Thus, learning from virtual objects may be more spatially demanding than learning from real objects. This raises the question of whether it is possible to augment virtual models in ways that mitigate the challenge of using these models and developing 3-D mental representations from them.

Can Virtual Objects Be Designed to Mitigate Spatial Demands on Learning?

The identification of an object's reference frame is a common process in theories of both object recognition and mental rotation (Ballaz, Boutsen, Peyrin, Humphreys, & Marendaz, 2005; Graf, 2006; Marr, 1982; Marr & Nishihara, 1992). We propose that manual rotation of virtual objects may be particularly difficult when the object's reference frame is difficult to establish. Establishing the viewed object's reference frame may require identifying the object's main axes (Marr, 1982), identifying distinguishable features of the object (Corballis, 1988; Hayward, Zhou, Gauthier, & Harris, 2006; Mitsumatsu & Yokosawa, 2002), or both (Humphreys & Riddoch, 1984, 2006). The reference frame may be challenging to determine when the orientation of a viewed object is such that the major axes are not discernible or distinguishable features of the object are occluded. Under these circumstances, viewers might be aided by assistance with visualizing the viewed object's main axes, recognizing distinguishable features, or both.

In this article, we examine how orientation references—visible lines overlapping the object's major axes—help learners manipulate virtual models of anatomy during learning and consequently help learners develop 3-D mental representations of anatomy. Orientation references offer both a visually salient indicator of the viewed object's main axes and distinguishable features that might aid in establishing the object's reference frame. We propose that orientation references mitigate the disorientation effects that people experience when manipulating virtual objects. Lowering the effort involved in object manipulation, in turn, should allow for more effort to be invested in gaining visual and spatial knowledge of the object.

Adding orientation references, however, may provide potential disadvantages as well as advantages to the learner. One potential disadvantage may be that the orientation references act as a crutch to the learner. Orientation references are highly salient artificial devices that attract the learner's attention. Participants may attend to the orientation references to the exclusion of the relevant anatomical features that they are intended to learn. It is also possible that learners build reliance on the orientation references such that they later cannot recognize objects or form effective mental representations when orientation references are not present.

In two experiments, we investigated the effects of providing orientation references, both on manual rotation of a virtual anatomical object and on learning the structure of that object. First, we measured speed, accuracy, and directness of rotation as participants performed a manual rotation task in which they attempted to match the orientation of a virtual anatomical object to a target orientation while also noting specific anatomical features of the object (i.e., the learning phase). These three dependent measures allowed us to quantify the success (accuracy), the effort (response time), and the efficiency (directness) of manually rotating the virtual object. Second, we measured learning performance by a task in which participants had to later identify anatomical features from different orientations of the bone model (i.e., the assessment phase).

We made two predictions. First, we predicted that providing orientation references would lead to more accurate, faster, and more direct manual rotation of an object to match a target orientation. Second, we predicted that orientation references would help participants learn the anatomy. We were particularly interested in whether these predictions would hold for low-spatial-ability learners.

Experiment 1: Noncanonical Axes

In Experiment 1, we tested our predictions by asking students to match target orientations as they learned anatomical features of a bone and then take a test to identify anatomical features from different orientations. The manual rotation trials in this experiment were designed to be difficult in that they involved rotations around different noncanonical axes (i.e., axes not orthogonal to the environment or main axes of the bone) and relatively large angles of rotation ($M = 130.9°$, $SD = 34.0°$).

Method

Participants. The participants were 83 college students ($M =$ 19.2 years, $SD = 1.1$) recruited from the Psychology Department Subject Pool at the University of California, Santa Barbara. Seven participants were excluded from the analysis because of equipment malfunction, experimenter error, or failure to follow directions, leaving 75 participants (30 men, 45 women) in the analysis.

Design. The study followed a 2 × 2 between-subjects design, with orientation reference (orientation reference vs. control) and spatial ability (high vs. low) as variables. Seventeen high-spatial-ability and 21 low-spatial-ability students served in the orientation reference group, and 19 high-spatial-ability and 18 low-spatial-ability students served in the control group. High- and low-spatial-ability groups were defined by a median split ($Mdn = 28$) of the participants' scores on the Vandenberg–Kuse Mental Rotation Test (Vandenberg & Kuse, 1978). These groups did not differ in self-reported bone anatomy knowledge. The dependent measures consisted of accuracy, response time, and directness on an object manipulation performance task, as well as accuracy on a feature identification posttest.

Materials and equipment. The materials included two versions of a manipulatable computer model of a bone, a two-page booklet describing anatomical features of the bone for the learning phase, a manual rotation battery consisting of 40 sheets of paper displaying target orientations of the bone, and 4 sheets of paper reminding students of the anatomical features of the bone during the rotation trials, a posttest consisting of 40 sheets of paper displaying bone orientations, a background knowledge questionnaire, and a mental rotation test (Vandenberg & Kuse, 1978).

The computer model was a virtual 3-D rendering of the human sixth cervical vertebra as shown in Figure 2. The model was rendered by Visible Productions, Inc., Fort Collins, Colorado from the Visual Human Project Database sponsored by the National Library of Medicine–National Institutes of Health. The model was displayed to participants with the Vizard 2.5 virtual reality program developed by WorldViz, LLC (Santa Barbara, CA), and was manipulated by participants with the InertiaCube2 three degree-of-freedom interface developed by InterSense, Inc. (Bedford, MA). The InertiaCube2 interface, sealed in a 2-in. (5.1-cm) diameter rubber ball, provided a temporal resolution of 10 ms, with an angular resolution of 0.01° root mean square deviation and was capable of measuring movement rates up to 1,200° per second.

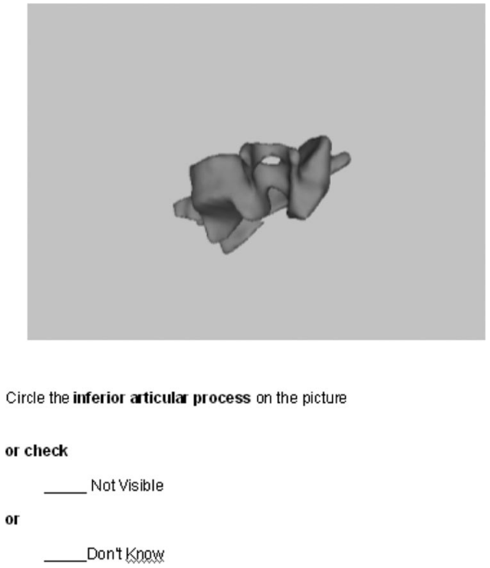
The two versions of the bone model differed in the presence or absence of orientation references (see Figure 1). In the starting orientation, the bone model was always positioned with the dorsal spinous process at top and the right transverse process at the right side of the image. In its natural orientation within the human spine, this represents a view from below looking up toward the head. For the orientation reference condition, colored poles were added to the bone model to make the vertical and horizontal canonical axes visually salient to the participant. A blue pole extending from the top center of the bone model showed the vertical axis. A red pole extending from the center of the right side showed the horizontal axis. The two poles intersected at the bone's pivot point. Participants sat approximately 28 in. (71.1 cm) from the monitor, and the stimuli subtended a maximum visual angle of 14° for the control and 18° for the orientation reference condition but varied depending on the orientation of the virtual object. The size and length of the poles were chosen so as to make them readily viewable at diverse orientations of the bone, and the difference in visual angle was due to the addition of these poles (orientation references). The size of the bone model was identical in the two conditions.

The pretraining booklet was a two-page (8.5- by 11-in. [21.6- × 27.9-cm] sheets) description with an illustration of the anatomical features of the bone. The purpose of the booklet was to provide learners with names and general locations of structural features that they would need when rotating the virtual bone and when completing the posttest. The left-hand page included a 257-word description of the bone and five anatomical features (see Appendix). The right-hand page included a labeled illustration with the five anatomical features that were described on the left-hand page (see Figure 2). The information was printed on facing pages and could be viewed without turning the page.

Twenty target orientations illustrated on 8.5- by 11-in. sheets of paper were used for the manual rotation trials. Figure 3 illustrates the information given to participants for a typical manual rotation trial. One target orientation was represented on a single sheet with two illustrations. The top illustration always displayed the bone in the starting orientation, which was the canonical orientation, and the bottom illustration showed the bone in 1 of 20 different target orientations. Both illustrations included the name of one anatomical structure and an arrow pointing to that structure. The target orientations were determined by generating three random numbers between 0 and 359 for the separate rotation angles around the object's three canonical axes in the order yaw (i.e., vertical axis), pitch (i.e., horizontal axis perpendicular to the viewer's line of sight), then roll (i.e., horizontal axis parallel to the viewer's line of sight). Once determined, actual target orientations were adjusted to bring both orientation reference poles into view if one or both were completely occluded by the body of the bone model. Trials were blocked, and each set of 20 target orientations was given twice in the same order, for a total of 40 trials.

Four pages containing text and diagram descriptions reminding the participant of bone anatomy were interleaved every 10 trials with the 40 target orientation pages. The purpose of these sheets was to emphasize that learning the bone anatomy was important and to provide the participants with the opportunity to verify the names of the target features. These descriptions, provided on 8.5- by 11-in. sheets, were placed at the beginning and after every 10th trial page. All descriptions were identical and illustrated the bone at the top of the page, with a 144-word text description at the bottom. The illustration was labeled with the five anatomical structures described in the two-page pretraining booklet, and the text was an abbreviated version of the description printed in the two-page booklet. The illustration for the orientation reference group included colored poles, and the illustration for the control group did not.

The 40 posttest feature identification pages, each showing one orientation of the bone, were printed on an 8.5- by 11-in. sheet of paper, as shown in Figure 4. The purpose of these sheets was to test learners' ability to recognize features from various orientations. Half of the set showed the bone in the 20 target orientations used during the rotation phase of the experiment (practiced orientations), and half of the set showed 20 bone orientations that had not been used as target orientations (unpracticed orientations). The practiced and unpracticed orientations were randomly mixed. The bone illustrations in the posttest did not include orientation references and were not labeled. Below each bone illustration was text asking the participant to circle a specific bone feature. An equal number of questions pertained to each of the five features taught in the experiment. Participants were also allowed to mark a checkbox if they could not see the requested structure or if they did not know where it was on the illustrated bone.



Circle the **inferior articular process** on the picture

or check

_____ Not Visible

or

_____Don't Know

Figure 4. An example feature identification accuracy question.

A background knowledge questionnaire included two questions asking participants about their knowledge of bone anatomy. One question asked participants to indicate which of several anatomical structures they could identify (i.e., femur, scapula, phalanges, etc.), and the second asked participants to rate their knowledge of bone anatomy on a 5-point Likert scale. This short questionnaire was administered at the beginning of the experiment.

The Vandenberg–Kuse Mental Rotation Test is a standard measure of spatial ability with good construct validity. We selected this instrument because it most closely represents the nature of the cognitive process—depth rotation of a 3-D object—that participants were expected to perform in our experimental task.

Procedure. Participants were tested individually and were assigned alternately to the orientation reference or the control condition. The experiment was composed of three phases: (a) pretraining, (b) manual rotation trials, and (c) feature identification posttest. During the pretraining phase, participants were given written and oral instructions before completing the Vandenberg–Kuse Mental Rotation Test. Next, they were given 5 min to read a two-page anatomy training booklet describing and illustrating five anatomical structures (see Figure 2) located on the surface of the human sixth cervical vertebra. The orientation reference group received a version containing the bone illustration with colored poles (see Figure 1), and the control group received a version containing the bone illustration without the colored poles. Participants were informed that they would be tested on their knowledge of the described and illustrated information. Next, participants were given 3 min to use the InertiaCube2 interface and become comfortable with manipulating the computer model of the bone. The participants were instructed to manipulate the computer model into diverse orientations of their choosing and to identify the anatomical structures illustrated in the anatomy booklet from these diverse orientations. They were again informed that they eventually would be tested on their knowledge of the bone.

During the manual rotation phase of the experiment, participants were seated in front of the computer monitor with the 40 sheets of paper containing two sets of the 20 target orientations. Participants were instructed to use the interface to move the computer model of the bone to "quickly and accurately" match each target orientation, which was intended to minimize the use of a discovery-by-wandering strategy. Participants were asked to say the name of the target feature, which was illustrated on the target page (see Figure 3), when they were satisfied that they had matched the orientation. Naming the target feature was intended to encourage the students to learn the structural anatomy. The canonical orientation of the bone was the starting orientation for all trials. Each trial began when the participant turned to a new target orientation, at which point the experimenter pressed a key on the computer keyboard to initiate a trial. Each trial ended when the participant said the name of the anatomy structure featured on the target page, at which point the experimenter pressed a key to terminate a trial. Learners were not provided with feedback. The computer captured the time and orientation data for later analysis. Participants were given as much time as they needed to move the computer model to match the illustrated target orientation. They were informed that when they received one of the four reminder pages (spaced evenly within the target set) they could take as much time as they wished to refresh and affirm their understanding of the bone anatomy.

During the feature identification posttest phase of the experiment, participants were given the posttest identification sheets (see Figure 4) and asked to mark with a circle or an arrow the specific location of a requested anatomical feature. Alternatively, they could check a box on the page if they could not see the requested feature or if they did not know the requested feature. Participants were allowed 30 s to complete each trial, and the next trial was presented at the end of this time period. We judged 30 s to be a sufficient time period to identify a single feature if the learners had actually learned the structural anatomy. Participants were debriefed and thanked for their participation after they completed the posttest.

Scoring. Accuracy for the manual rotation task was calculated as the average angular difference (degrees) between the target orientation and a participant's final orientation for the 40 trials (possible range = 0° to 180°).[1] Response time for the manual rotation task was calculated as time (in seconds) from a participant's first view of the target orientation to the participant's verbal statement that they had successfully matched the target orientation (averaged over 40 trials). Directness of rotation was calculated as the average integral of the object's angular distance from the target over time (degree-seconds) for 40 trials. The directness measure captures whether the participant rotated the object by the shortest path between the start orientation and the target orientation. A low value on the directness measure represents a direct and fast movement of the object, and a high value on this measure represents an indirect path, a slower movement, or both.

Feature identification accuracy was measured as the proportion correct on 37 feature identification tasks.[2] Two reviewers independently scored the identification sheets; the correlation between their scores was high, $r(76) = .91$, $p < .001$. Discrepancies in the scores between the two scorers were resolved by a third scorer.

Results and Discussion

Data analysis. Data were analyzed with separate two-way analyses of variance (ANOVAs) examining the effects of orientation references and spatial ability on each of the dependent measures: accuracy, response time, directness, and proportion of feature identification errors.[3] Table 1 lists the mean and standard deviation for each of the treatment groups on each of the four dependent measures.

Do participants with orientation references manually rotate a virtual object more accurately? The first portion of Table 1 summarizes the mean target matching accuracy (i.e., the angular deviation from the target orientation) of the four conditions in Experiment 1. The orientation reference group was significantly more accurate than the control group, $F(1, 71) = 7.62$, $MSE = 3{,}218.63$, $p = .01$, $d = 0.63$, and participants with higher spatial ability were significantly more accurate than participants with lower spatial ability, $F(1, 71) = 5.32$, $MSE = 2{,}247.88$, $p = .02$, $d = 0.46$. The interaction was not significant, $F(1, 71) = 0.05$, $MSE = 19.19$, $p = .83$. Thus, for both high- and low-spatial-ability learners, orientation references improved accuracy on the manual rotation tasks.

Do participants with orientation references manually rotate a virtual object faster? The second portion of Table 1 summarizes the mean response times of the four groups in Experiment 1. The orientation reference group responded significantly faster than the control group, $F(1, 71) = 4.31$, $MSE = 166.82$, $p = .04$, $d = 0.41$, and participants with higher spatial ability performed significantly faster than participants with lower spatial ability, $F(1, 71) = 11.05$, $MSE = 427.92$, $p < .001$, $d = 0.72$. The interaction was not significant, $F(1, 71) = 0.79$, $MSE = 30.63$, $p = .38$. Thus, for both high- and low-spatial-ability learners, orientation references improved speed on the manual rotation task.

Do participants with orientation references manually rotate a virtual object more directly? The third portion of Table 1 summarizes the mean directness of the four groups in Experiment 1. The orientation reference group was significantly more direct than the control group, $F(1, 71) = 20.02$, $MSE = 6{,}360.98$, $p < .001$, $d = 0.86$, and participants with higher spatial ability were significantly more direct than participants with lower spatial ability in moving the virtual object from the starting orientation to the target orientation, $F(1, 71) = 24.50$, $MSE = 7{,}784.09$, $p < .001$, $d = 0.79$. The interaction was not significant, $F(1, 71) = 0.28$, $MSE = 87.61$, $p = .60$. Thus, for both high- and low-spatial-ability learners, orientation references improved directness on the manual rotation task.

Does providing participants with orientation references lead to better learning of 3-D anatomy? Does learning transfer to unpracticed orientations? The fourth portion of Table 1 summarizes the mean proportion of correct feature identification questions in the posttest for the four groups in Experiment 1. A 2 × 2 × 2 mixed design ANOVA was conducted, with orientation references (orientation references vs. no orientation references) and spatial ability (high vs. low) as between-subjects variables and posttest orientation (practiced vs. unpracticed) as a within-subject variable. There was not a significant effect of orientation references, $F(1, 71) = 1.08$, $MSE = 0.02$, $p = .30$, but participants with higher spatial ability identified significantly more object features than did participants with lower spatial ability, $F(1, 71) = 13.61$, $MSE = 0.25$, $p < .001$, $d = 0.81$. These results are qualified by a significant interaction, $F(1, 71) = 5.92$, $MSE = 0.11$, $p = .02$. Contrast analyses revealed that participants with lower spatial ability in the orientation reference group correctly identified more object features, $F(1, 71) = 6.27$, $MSE = 0.06$, $p = .02$, $d = 0.76$, than did participants with lower spatial ability in the control group, but the

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[1] Accuracy in matching the bone model to the target orientations was measured in *quaternions*, a base 4 hypercomplex number set used to measure the orientation of objects in three-dimensional space (Kuipers, 1999). Using quaternions, one can measure the difference between two orientations as a single value in degrees. Directness in moving the virtual bone was measured as the integral of the accuracy by time interaction for each trial. The directness measure incorporates both a spatial and a temporal component. Maximally efficient trials would consist of a minimal path of motion from the start to the target orientation, with a time course restricted only by biomechanical limits of the hand. An inefficient trial might incorporate a wandering path of motion, low accuracy in matching the target orientation, slow hand movements, or all three.

[2] Three posttest orientations (one practiced and two unpracticed) were dropped from the analysis because they could not be reliably scored.

[3] The homogeneity of variance assumption of the ANOVA was not met for the analysis of the accuracy or directness data. A rank transformation technique was applied to the data (Conover & Iman, 1981) and it was reanalyzed. Statistics for the transformed data are reported.

Table 1

Means and Standard Deviations on Manual Rotation Trials and Feature Identification by Treatment Group and Spatial Ability for Experiment 1

Measure/spatial ability	Orientation reference *M* (*SD*)	Control *M* (*SD*)
Accuracy (degree)		
High spatial ability	19.55 (8.7)	29.55 (17.8)
Low spatial ability	26.91 (15.2)	39.62 (22.1)
Response time (seconds)		
High spatial ability	12.73 (3.8)	14.44 (6.3)
Low spatial ability	16.24 (4.9)	20.52 (8.8)
Directness (degree-seconds)		
High spatial ability	857.8 (299.5)	1,204.1 (566.7)
Low spatial ability	1,175.3 (296.3)	1,911.3 (822.3)
Feature identification, total (proportion correct)		
High spatial ability	0.78 (0.11)	0.81 (0.08)
Low spatial ability	0.75 (0.06)	0.67 (0.13)
Feature identification, old (proportion correct)		
High spatial ability	0.77 (0.11)	0.79 (0.08)
Low spatial ability	0.75 (0.07)	0.66 (0.14)
Feature identification, new (proportion correct)		
High spatial ability	0.78 (0.13)	0.82 (0.08)
Low spatial ability	0.74 (0.09)	0.68 (0.14)

Note. Participants were tested on 18 practiced (old) and 19 unpracticed (new) orientations.

effect of orientation references was not significant for high-spatial-ability individuals, $F(1, 71) = 0.93$, $MSE = 0.01$, $p = .34$. Thus, orientation references improved learning of anatomy for low-spatial-ability individuals, whereas learning was good with and without orientation references for high-spatial-ability individuals.

In addition, the within-subject effect of posttest orientation (practiced vs. unpracticed) was not significant, $F(1, 71) = 1.05$, $MSE = 0.01$, $p = .31$, indicating that feature identification transferred from practiced to unpracticed orientations. The within-subject interactions with spatial ability and orientation references were also not significant. Thus, practicing with orientation references may help learners identify features from unfamiliar orientations when orientation references are not available.[4]

Further, the correlations between posttest scores and manual rotation measures for Experiment 1 showed a strong negative correlation for response time, $r(76) = -.33$, $p = .004$, and rotation directness, $r(76) = -.46$, $p < .001$, but not for rotation accuracy, $r(76) = -.15$, $p = .18$. Participants who rotated the model in less time and more directly generally did better on the posttest, but participants who more accurately matched the target orientation were not necessarily better on the posttest. These results support the idea that if people are burdened by the task of rotating the computer model, they learn less about the anatomy.

In summary, the results support our first prediction that participants rotate a virtual object more accurately, faster, and more directly when given orientation references than when not given orientation references. On average, performance of the orientation reference group was 10.8° more accurate, 2.7 s faster, and 514.8 degree-seconds more direct than the control group when manually rotating the virtual object to match a target orientation.

Further, the results show that manual rotation performance is related to spatial ability. Participants with higher spatial ability rotated a virtual object more accurately, faster, and more directly than did participants with lower spatial ability.

Finally, the results support our second prediction in that orientation references helped participants learn the anatomy of the bone. Importantly, this difference in learning attributable to orientation references was greatest for low-spatial-ability participants. Overall, participants with lower spatial ability in the orientation reference group correctly identified more features than did those in the control group.

Contrary to our concern that orientation references could act as a crutch to performance while distracting participants from attending to the intended feature information, results showed that participants were able to use the orientation references and still gain the necessary feature knowledge intended by the training. This was especially true among participants with lower spatial ability who are more likely to be burdened by added spatial content. We propose that the orientation reference effect is due to a decrease in the cognitive load (Sweller, van Merrienboer, & Paas, 1998) among participants with lower spatial ability. Without orientation references, such participants are more likely to be burdened by the task of perceiving, interpreting, and matching the orientation of a complex object while also attempting to remember the names of

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[4] Posttest feature identification scores were regressed on orientation references and spatial ability. These predictors accounted for 20% of the variance in feature identification for practiced orientations, a significant effect, $F(3, 71) = 5.78$, $p = .001$. Orientation references ($b = .49$, $p = .015$), spatial ability ($b = .55$, $p < .001$), and their interaction ($b = -.44$, $p = .048$) demonstrated significant effects. For unpracticed orientations, these predictors accounted for 23% of the variance in feature identification, $F(3, 71) = 7.19$, $p < .001$. Spatial ability ($b = .55$, $p < .001$) had a significant effect in this analysis, but orientation references and their interaction did not. These results reinforce our earlier finding that lower spatial ability participants received a learning benefit from orientation references but raise the question of whether this effect transfers to unpracticed orientations.

unfamiliar features. Providing orientation references relieves the cognitive load, allowing learners to better encode object features, which contributes to the building of more complete and coherent mental representations of the attended object.

Experiment 2: Canonical Axes

Experiment 1 demonstrated that orientation references promote faster, more accurate, and more direct movement of a virtual object on the manual rotation task while allowing participants with lower spatial ability to better encode object features as indicated on the anatomy posttest. The stimuli used in Experiment 1 were generated by rotating the object by large angles ($M = 130.9°$, $SD = 34.0°$) around noncanonical axes. When the axis of rotation is not aligned with the object, the observer, or the environment, object orientations are generally more difficult to imagine and more difficult to recognize (Pani, 1993; Shiffrar & Shepard, 1991). Mental rotation is also more difficult for larger angles (Shepard & Metzler, 1971). Because of the suggested importance of mental rotation in performing manual rotation tasks (Ruddle & Jones, 2001; Wexler et al., 1998; Wohlschläger, 2001; Wohlschläger & Wohlschläger, 1998), performance in our manual rotation task should have been highly influenced by the challenging nature of the target orientations.

People may not be burdened by rotations around canonical axes and smaller angles because, evidence suggests, these conditions are generally easier to imagine (Pani, 1993). In Experiment 2, we investigated whether orientation references are helpful for these simpler rotations and whether rotations around canonical axes and smaller angles lead to equivalent mental representations of 3-D objects. Thus, in Experiment 2, we sought to replicate and extend the results of Experiment 1 by examining how effects of orientation references are moderated by the axis and angle of rotation. Overall, the manual rotation tasks were easier in Experiment 2 than in Experiment 1.

Method

Participants. The participants were 59 college students ($M = 20.0$ years, $SD = 1.7$) recruited from the Psychology Department Subject Pool at the University of California, Santa Barbara. One participant was excluded for failure to follow directions, leaving 58 participants (19 men, 39 women) in the analysis.

Design. The study followed a 2 × 2 × 2 × 2 mixed design, with orientation reference (orientation references vs. control) and spatial ability (high vs. low) as between-subjects variables and axis of rotation (canonical vs. noncanonical) and angle of rotation (small vs. large) as within-subject variables. A total of 29 students (17 high spatial ability, 12 low spatial ability) served in the orientation references group, and 29 students (17 high spatial ability, 12 low spatial ability) served in the control group. High versus low spatial ability was defined by a split of the participants' spatial ability scores on the Vandenberg–Kuse Mental Rotation Test (Vandenberg & Kuse, 1978). Participants scoring above a value of 28 were designated as having high spatial ability, and those scoring at or below 28 were considered to have low spatial ability.[5] The groups did not differ in self-reported bone anatomy knowledge. The dependent measures were the same as in Experiment 1.

Materials and equipment. The materials for Experiment 2 were identical to those for Experiment 1, with the exception of the target orientations used for the manual rotation trials. The 44 target orientations for Experiment 2 were composed of 11 rotations in 30° increments around the three canonical axes (Figure 5) and a noncanonical axis. Canonical axes comprised yaw (vertical axis), pitch (horizontal axis in the picture plane), and roll (horizontal axis parallel to the line of site). The noncanonical axis was 45° between the pitch and roll axes pointing out of the screen to the right of the observer and 45° above the horizontal plane (see Figure 5). All axes of rotation shared a common point at the origin, which was the pivot point for the virtual bone model. Small angle rotations were 30°, 60°, or 90°, and large angle rotations were 120°, 150°, and 180°.

Procedure. The procedure for Experiment 2 was identical to that of Experiment 1 except that only 15 s were allowed for each feature identification trial (because it was determined that a time of 30 s was excessive in Experiment 1).

Scoring. Accuracy, response time, directness, and feature identification accuracy were measured in the same manner as in Experiment 1. Two reviewers independently scored the identification sheets; the correlation between the scores was high, $r(58) = .94$, $p < .001$). Discrepancies between the scores of the two scorers were decided by a third rater.

Results and Discussion

Data analysis. Data were analyzed with separate 2 × 2 × 2 × 2 mixed-design ANOVAs comparing the presence and absence of orientation references, high and low spatial ability, canonical and noncanonical axes of rotation, and small and large rotation angles on each of the dependent measures: accuracy, response time, directness, and proportion correct on feature identification.[6] The means and standard deviations for the treatment groups on each of the four dependent measures are listed in Table 2.

Do participants with orientation references manually rotate a virtual object more accurately? The first portion of Table 2 summarizes the mean target matching accuracy for Experiment 2. For the between-subject effects, the orientation reference group was significantly more accurate than the control group, $F(1, 54) = 90.98$, $MSE = 0.53$, $p < .001$, $d = 2.20$, and participants with higher spatial ability were significantly more accurate than participants with lower spatial ability, $F(1, 54) = 5.88$, $MSE = 0.03$, $p = .02$, $d = 0.34$. The interaction was not significant, $F(1, 54) = 1.85$, $MSE = 0.01$, $p = .18$. As in Experiment 1, for both high- and low-spatial-ability learners, orientation references improved accuracy on the manual rotation task.

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[5] The median score on the Vandenberg–Kuse Mental Rotation Test in Experiment 2 was 34. For consistency with Experiment 1, we used a score of 28 to separate higher and lower spatial ability participants in Experiment 2. The statistical results did not differ on the basis of the spatial ability grouping score.

[6] The homogeneity of variance assumption of the ANOVA was not met for the analysis of the accuracy or directness data. A reciprocal square root (1/square root of the original value) transformation was applied to the data (Field, 2005), which were then reanalyzed. Statistics for the transformed data are reported.

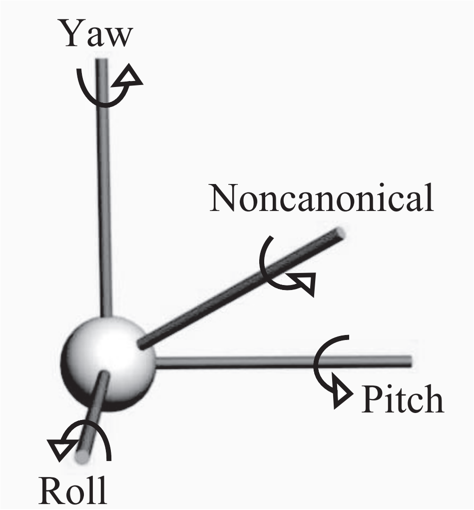

Figure 5. In Experiment 2, target orientations were developed as rotations of 30° around the three canonical axes (i.e., yaw, pitch, and roll) and a noncanonical axis.

For the within-subject effects, participants were significantly more accurate with rotations around canonical axes than with rotations around the noncanonical axis, $F(1, 54) = 47.02$, $MSE = 0.06$, $p < .001$; students were also significantly more accurate with small-angle rotations than with large-angle rotations, $F(1, 54) = 28.57$, $MSE = 0.03$, $p < .001$. Further, there was a significant interaction of axis by angle, $F(1, 54) = 16.53$, $MSE = 0.02$, $p = .02$. Contrast analyses revealed that performance on small-angle rotations was significantly more accurate than performance on large-angle rotations around the canonical axes, $F(1, 54) = 43.36$, $p < .001$, but that accuracy did not differ between small and large angles of rotations around the noncanonical axis, $F(1, 54) = 0.67$, $p = .42$.

The interaction of angle by orientation reference was also significant, $F(1, 54) = 11.25$, $MSE = 0.01$, $p = .001$. Contrast analyses revealed that orientation references eliminated the effect of angle; no difference in accuracy was evident for small- and large-angle rotations among the orientation reference group, $F(1, 54) = 1.98$, $p = .17$, whereas performance on large-angle rotations was significantly less accurate than that on small-angle rotations for the control group, $F(1, 54) = 37.83$, $p < .001$. Further, there was a significant interaction of axis by angle by orientation reference, $F(1, 54) = 5.66$, $MSE = 0.01$, $p = .02$. Contrast analyses revealed that in the orientation reference condition, accuracy was no different for large-angle rotations around canonical compared with noncanonical axes. In short, orientation references improved accuracy on difficult, but not on easy, manual rotation tasks. No other interactions were significant.

Do participants with orientation references manually rotate a virtual object faster? The second portion of Table 2 summarizes the mean response times for Experiment 2. For the between-subjects effects, the orientation reference group was not significantly faster than the control group, $F(1, 54) = 0.14$, $MSE = 9.51$, $p = .71$, and participants with higher spatial ability were not significantly faster than participants with lower spatial ability, $F(1, 54) = 2.56$, $MSE = 171.39$, $p = .12$. The interaction was not significant, $F(1, 54) = 1.53$, $MSE = 102.61$, $p = .22$. Contrary to the results of Experiment 1, orientation references did not improve speed on the manual rotation task in Experiment 2.

Within-subject effects indicated that large-angle rotations took longer than did small-angle rotations, $F(1, 54) = 27.65$, $MSE = 330.74$, $p < .001$, and that rotations around the noncanonical axis were significantly slower than rotations around the canonical axes, $F(1, 54) = 71.96$, $MSE = 754.69$, $p < .001$. Finally, the interaction of axis by angle was significant, $F(1, 54) = 6.00$, $MSE = 42.87$, $p = .02$. Contrast analyses indicate that, although performance on large-angle trials was consistently slower than performance on small-angle trials, the mean difference between large and small angles was greater for rotations around the noncanonical axis than for those around the canonical axes. No other interactions were statistically significant. These effects are consistent with known effects of axis and angle on mental rotation (Pani, 1993; Parsons, 1995; Shiffrar & Shepard, 1991).

Do participants with orientation references manually rotate a virtual object more directly? The third portion of Table 2 summarizes mean directness values for Experiment 2. For the between-subjects effects, the orientation reference group performed manual rotations more directly than did the control group, $F(1, 54) = 24.09$, $MSE = 0.01$, $p < .001$, $d = 1.20$, and participants with higher spatial ability rotated more directly than did participants with lower spatial ability, $F(1, 54) = 5.50$, $MSE = 0.001$, $p = .02$, $d = 0.65$. The interaction of orientation reference by spatial ability was not significant, $F(1, 54) = 1.43$, $MSE = 0.0003$, $p = .24$. As in Experiment 1, orientation references improved directness on manual rotation tasks for both high- and low-spatial-ability learners.

Within-subject comparisons indicated that rotations around the noncanonical axis were significantly less direct than rotations around the canonical axes, $F(1, 54) = 118.95$, $MSE = 0.004$, $p < .001$, and participants were significantly more direct in rotations around small angles than in rotations around large angles, $F(1, 54) = 31.40$, $MSE = 0.01$, $p < .001$. Further, the interaction of axis by angle was significant, $F(1, 54) = 9.13$, $MSE = 0.0002$, $p = .004$. Contrast analyses revealed that the mean difference between small and large angles was greater for rotations around the noncanonical axis (694 degree-seconds) than for rotations around the canonical axes (461 degree-seconds).

The interaction of angle by orientation reference was significant, $F(1, 54) = 9.60$, $MSE = 0.0004$, $p = .003$. Contrast analyses revealed that the mean difference between the orientation reference and control groups was greater for rotations around the large angles (478.73 degree-seconds) than for rotations around the small angles (288.61 degree-seconds). In short, orientation references improved directness to a greater extent for difficult than for easy manual rotation tasks. Finally, the interaction of angle by spatial ability was significant, $F(1, 54) = 4.83$, $MSE = 0.0002$, $p = .03$. Contrast analyses revealed that the high-spatial-ability group performed better than the low–spatial-ability group on small angles but not on large angles. No other interactions were statistically significant.

Does providing participants with orientation references lead to better learning of three-dimensional anatomy? The fourth portion of Table 2 summarizes the mean proportion correct score for feature identification in the posttest phase of Experiment 2. For the between-subjects effects, feature identification was not significantly affected by orientation references in this experiment F(1,

Table 2

Means and Standard Deviations on Manual Rotation Trials and Feature Identification by Treatment Group and Spatial Ability for Experiment 2

Measure, spatial ability, axis, and angle	Orientation reference *M* (*SD*)	Control *M* (*SD*)
Accuracy (degrees)		
High spatial ability		
Canonical		
Small angle	10.11 (2.58)	26.57 (13.04)
Large angle	15.03 (6.78)	44.49 (22.59)
Noncanonical		
Small angle	15.82 (4.88)	47.10 (23.13)
Large angle	14.50 (6.72)	62.01 (35.72)
Low spatial ability		
Canonical		
Small angle	14.70 (6.48)	27.28 (12.95)
Large angle	17.26 (5.68)	47.60 (16.73)
Noncanonical		
Small angle	22.15 (5.63)	48.51 (28.08)
Large angle	20.83 (12.70)	75.44 (34.27)
Response time (seconds)		
High spatial ability		
Canonical		
Small angle	8.61 (2.69)	7.86 (3.04)
Large angle	11.15 (4.79)	9.23 (2.72)
Noncanonical		
Small angle	10.16 (3.74)	10.52 (4.47)
Large angle	14.52 (7.19)	13.08 (5.34)
Low spatial ability		
Canonical		
Small angle	8.98 (4.19)	10.18 (3.43)
Large angle	10.00 (3.22)	11.46 (3.52)
Noncanonical		
Small angle	12.56 (7.57)	13.54 (5.17)
Large angle	14.48 (5.74)	17.89 (8.39)
Directness (degree-seconds)		
High spatial ability		
Canonical		
Small angle	292.27 (90.91)	414.27 (201.73)
Large angle	770.26 (345.22)	901.43 (323.23)
Noncanonical		
Small angle	439.32 (276.34)	719.56 (360.53)
Large angle	1,082.36 (659.59)	1,472.15 (721.66)
Low spatial ability		
Canonical		
Small angle	369.53 (257.81)	620.29 (314.11)
Large angle	693.80 (201.76)	1,159.28 (371.46)
Noncanonical		
Small angle	624.63 (478.54)	1,126.08 (574.43)
Large angle	1,100.55 (499.32)	2,029.05 (735.19)
Feature identification (proportion correct)		
High spatial ability	0.72 (0.07)	0.69 (0.09)
Low spatial ability	0.66 (0.17)	0.69 (0.06)

54) = 0.01, *MSE* = 0.00006, $p = .94$. Furthermore, there was no significant effect of spatial ability on feature identification in this experiment, $F(1, 54) = 1.11$, *MSE* = 0.01, $p = .30$. Finally, the interaction of orientation references and spatial ability was not significant, $F(1, 54) = 1.06$, *MSE* = 0.01, $p = .31$. Unlike the results of Experiment 1, orientation references did not improve performance on the anatomy posttest.[7]

The correlations between posttest scores and manual rotation measures for Experiment 2 replicated the results of Experiment 1. There were strong negative correlations of both response time, $r(58) = -.41$, $p = .002$, and rotation directness, $r(58) = -.36$, $p = .01$, with posttest performance, but again rotation accuracy, $r(58) = .05$, $p = .73$, was not significantly correlated with posttest performance. Participants who rotated the model in less time and more directly generally did better on the posttest, consistent with the idea that if people are burdened by the task of rotating the computer model, they learn less anatomy.

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[7] Regression of posttest feature identification scores on orientation references and spatial ability did not yield different results.

In summary, the results of Experiment 2 support our first prediction that orientation references facilitate manual rotation. When manually rotating a virtual object, participants who used orientation references were 31.08° more accurate and 383.67 degree-seconds more direct than those in the control group. In contrast to the results of Experiment 1, participants in the orientation reference group were not faster than participants in the control group on the task.

The lack of an orientation reference effect for response time may be due to the less challenging nature of the orientations used in Experiment 2. Whereas the stimuli used in Experiment 1 all involved large-angle rotations ($M = 130.5°$, $SD = 34.0°$) around multiple noncanonical axes, many of the stimuli used in Experiment 2 were small-angle rotations (30°, 60°, 90°), and three of the four axes were canonical; therefore, participants would have been expected to be faster at imagining and performing such rotations. Abundant research has shown that mental rotation around large angles or noncanonical axes are generally more challenging to perform (Pani, 1993; Parsons, 1995; Shepard & Metzler, 1971; Shiffrar & Shepard, 1991). Our results suggest that this is also the case with the manual rotation of objects under similar conditions.

The results of Experiment 2 partially replicate the results from Experiment 1 suggesting that manual rotation performance is related to spatial ability. Participants with higher spatial ability were significantly more accurate (4.77°) than participants with lower spatial ability and 203.95 degree-seconds more direct, but there was no significant difference in speed of manual rotation performance between participants with higher and lower spatial ability on the simpler rotations in this experiment.

In Experiment 2, we investigated the effects of angle (small vs. large) and axis (canonical vs. noncanonical) on rotation and learning performance. The results show that large-angle manual rotations were much more challenging than small-angle manual rotations and that rotations around noncanonical axes were much more challenging than rotations around canonical axes. For example, when rotating the object around the noncanonical axis, participants were 12.91° less accurate, 421.57 degree-seconds less direct, and 3.66 seconds slower than when rotating the object around canonical axes. In addition, participants were 10.61° less accurate, 575.37 degree-seconds less direct, and 2.43 s slower when performing large-angle rotations than when performing small-angle rotations. The results also show that the challenge of large angles and noncanonical axes was diminished for the orientation reference group, replicating the results of Experiment 1. For example, the difference in accuracy for rotations around noncanonical versus canonical axes was 21.8° in the control group but 4.0° in the orientation reference group. Similarly, the difference in accuracy for large-angle versus small-angle rotations was 20.0° in the control group but 1.2° in the orientation reference group. The benefit of orientation references is mirrored in path directness measures. The difference in directness for rotations around noncanonical versus canonical axes was 562.89 degree-seconds in the control group but 280.25 degree-seconds in the orientation reference group. These differences were all statistically significant.

Our second prediction was that providing orientation references helps people learn 3-D anatomy. The results of Experiment 2 do not replicate the results of Experiment 1. The orientation reference group did not perform significantly differently than the control group in the proportion of features correctly identified, and participants with lower spatial ability did not significantly differ from participants with higher spatial ability.

Although learning performance was generally good (average of 75% correct in Experiment 1 and 69% correct in Experiment 2), a post hoc analysis revealed a significant difference between posttest feature identification in the two experiments, $t(137) = 3.06$, $p = .003$. This difference in learning between the experiments may be due to the relationship between the orientations used for the manual rotation trials and feature identification posttest in the two experiments. In Experiment 1, the orientations used for the manual rotation phase were equally challenging to the orientations used in the feature identification posttest (i.e., large-angle rotations around unique noncanonical axes). Further, half of the 40 posttest orientations were the same as those practiced in the manual rotation trials. In Experiment 2, participants performed simpler manual rotation trials (i.e., rotations in 30° increments around three canonical axes and one noncanonical axis) and were tested with more challenging orientations in the posttest, the same orientations used in Experiment 1. The observed decrease in learning performance between Experiments 1 (75% correct) and 2 (69% correct) could have resulted from practicing with simple orientations that did not prepare the participants for testing with more challenging orientations.

An alternative interpretation is that the better learning performance of Experiment 1 is due to a practice effect because half of the posttest orientations were practiced in the rotation trials. If this interpretation were correct, then posttest accuracy should have been significantly better for practiced orientations than for unpracticed orientations, which was not the case. We interpret the results as suggesting that practicing with simple orientations did not prepare participants when challenging orientations were given on the posttest.

General Discussion

In two experiments, we examined the effects of orientation references when individuals learned anatomy by manually rotating virtual 3-D anatomical models and paying attention to labeled features of those models. The goals of the project were to investigate whether orientation references help learners manually rotate a virtual object and whether orientation references help learners develop better mental representations during anatomy learning.

Are Orientation References Helpful?

Orientation references were shown to help learners rotate virtual objects more accurately and directly in both experiments. With the more challenging trials in Experiment 1, orientation references also helped learners rotate virtual objects more quickly. Low-spatial-ability individuals learned the anatomy better with orientation references under the challenging conditions in Experiment 1, whereas learning was otherwise equivalent with and without orientation references. In Experiment 1, orientation references reduced the differences in anatomical learning between participants with higher and lower spatial ability.

For Whom Are Orientation References Helpful?

Spatial ability played a significant role in our manual rotation task. Individuals with lower spatial ability, in comparison with those of higher spatial ability, had poorer performance when rotating the virtual object. This result is consistent with previous findings that low-spatial-ability individuals have difficulty manipulating and using 3-D virtual models (Cohen & Hegarty, 2007; Garg et al., 1999; Keehner et al., 2008; Luursema et al., 2006). Although one might argue that orientation references would be beneficial primarily for performance on manual rotation tasks by low-spatial-ability individuals, in fact, orientation references were helpful to both high- and low-spatial-ability individuals. This demonstrates that all learners of all levels of spatial ability can be challenged by 3-D virtual models, and orientation references offer a method of mitigating the demands of manipulating these virtual learning resources.

Spatial ability was a contributing factor to anatomical learning, consistent with previous research (Rochford, 1985). In Experiment 1, high-spatial-ability individuals in the control condition outperformed low-spatial-ability individuals in that condition. Interestingly, this difference was reduced in the orientation reference condition, suggesting that providing these aids alleviated difficulties faced by low-spatial-ability individuals in learning anatomy.

The poorer performance of lower spatial ability participants in the control conditions of these experiments may be due to difficulty recognizing the orientation of an object when its main axis is foreshortened or when distinguishable features are occluded. This effect may also be due to poor ability to mentally rotate the perceived object for comparison with a representation of that object from a different orientation. Finally, poor performance may be due to lower ability to mentally compare features in representations of the same object from different orientations. In our experiments, the comparison in manual rotation was one between different views of the object that were presented externally, whereas the comparison in the posttest feature recognition task occurred between a view of the object presented externally and the participant's internal mental representation. We propose that by providing orientation references, which clearly mark the orientation of the object, we reduced participants' cognitive load during the learning (manual rotation) phase of the experiment and consequently enabled them to construct more coherent mental representations, which they could then use to recognize features during the posttest trials.

When Are Orientation References Helpful?

A comparison of the results of Experiments 1 and 2 reveals that orientation references are most helpful under the most challenging conditions for both manual rotation and anatomical learning. First, orientation references had larger effects on both manual rotation and learning in Experiment 1 (which used large angles and noncanonical axes) than in Experiment 2. Second, in Experiment 2, orientation references helped more for rotations around noncanonical axes than for rotations around canonical axes. Third, in Experiment 2, orientation references helped more for large angles than for small angles.

Orientation references are therefore most helpful under conditions that are typical of medical practice. Medical professionals such as surgeons, radiologists, and nurses are often called upon to recognize anatomical structures from noncanonical orientations. Our research suggests that providing orientation references during learning will allow professionals to construct coherent mental representations that enable them to recognize features of anatomical structures from diverse perspectives. However, more work is needed to understand how this technique is effective over a long-term period.

It is interesting that manual rotation of virtual objects is affected by axis and angle of rotation, which are also performance challenges associated with mental rotation (Pani, 1993; Parsons, 1995; Shepard & Metzler, 1971; Shiffrar & Shepard, 1991). This supports the view that mental rotation is a component of manual rotation (Ruddle & Jones, 2001; Wexler et al., 1998; Wohlschläger, 2001; Wohlschläger & Wohlschläger, 1998). The fact that manual rotations around large angles and noncanonical axes were less accurate is somewhat surprising given that participants in our study had more than enough time and opportunity to perform and validate their actions.

How Are Orientation References Helpful?

Given the positive effects of orientation references in our experiments, it is important to consider the mechanisms by which they confer benefit. Our hypotheses were based on the importance of establishing an object's reference frame during recognition (Ballaz et al., 2005; Corballis, 1988; Graf, 2006; Hayward et al., 2006; Humphreys & Riddoch, 1984, 2006; Marr, 1982; Marr & Nishihara, 1992; Mitsumatsu & Yokosawa, 2002). This aspect of object recognition is relevant to both manual rotation of a virtual anatomical object and recognizing features of that object from different orientations. Our orientation references may aid participants by either (a) defining the main axes of the object or (b) offering visually salient and easily distinguishable features. The results of our study do not distinguish between these hypotheses but are consistent with both. Future research should evaluate whether visually salient and easily distinguishable features would be equally effective as orientation references if they did not define the main axes of the object.

Implications

Our research suggests that virtual learning resources may increase rather than diminish the burden imposed on low-spatial-ability learners in spatially demanding professions. Poorly designed virtual resources can impose an unnecessary yet preventable disadvantage for individuals who, if given adequate aids, may develop into successful practitioners. The orientation reference technique we explored in this research is an example of one way to minimize problems of low-spatial-ability learners when using virtual resources. With the spatial burden lightened by cognitive handles, such as the orientation references explored here, individuals may be better able to develop the skills and knowledge that they need to be successful in spatially demanding careers.

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(*Appendix follows*)

Appendix

Anatomical Features of the Human Sixth Cervical Vertebrae

The individual bones of your spinal column are the **vertebrae** (plural for *vertebra*). Each vertebra forms a bony ring, which creates a hollow tube when stacked one on top of another. Your vertebrae surround and protect your spinal cord and also provide a framework where muscles attach and where other bones join. Your muscles allow mobility and your joints allow flexibility.

Vertebrae have many parts that are divided into general structures called processes and foramina (plural for *foramen*). A **process** is a location on a bone where a muscle attaches or another bone meets to form a joint. A **foramen** is an opening or passage for nerves or blood vessels.

- The **spinous process** is the long bony projection on each vertebra. You can feel the spinous process on each bone if you run your hand down your back. The spinous process is just one location where your muscles attach to the vertebrae.
- The two **transverse processes** are on either side of your vertebrae and are locations where additional muscles attach.
- The **superior articular process** and **inferior articular process** form joints between adjacent vertebrae. The superior (upper) articular process of one vertebra meets the inferior (lower) articular process of an adjacent vertebra. These processes overlap each other to form two flexible joints, one on either side of the vertebrae.
- The **transverse foramen** is the opening on either side of your vertebrae. These two openings are where nerves bundles enter and exit your spinal cord to reach the rest of your body.

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Call for Nominations

The Publications and Communications (P&C) Board of the American Psychological Association has opened nominations for the editorships of **Experimental and Clinical Psychopharmacology, Journal of Abnormal Psychology, Journal of Comparative Psychology, Journal of Counseling Psychology, Journal of Experimental Psychology: Human Perception and Performance, Journal of Personality and Social Psychology: Attitudes and Social Cognition, PsycCRITIQUES, and Rehabilitation Psychology** for the years 2012–2017. Nancy K. Mello, PhD, David Watson, PhD, Gordon M. Burghardt, PhD, Brent S. Mallinckrodt, PhD, Glyn W. Humphreys, PhD, Charles M. Judd, PhD, Danny Wedding, PhD, and Timothy R. Elliott, PhD, respectively, are the incumbent editors.

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