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Individual Differences in Use of External Visualisations to Perform an Internal Visualisation Task

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SUMMARY

Thirty participants performed a novel spatial inference task, which required them to imagine and draw the cross section of a three-dimensional (3-D) object. While performing the task, participants could interactively control two computer visualisations (animations) of the object. There were large individual differences in how frequently participants used the computer visualisations, which were related to spatial ability. Use of the interactive visualisations was highly predictive of performance on the cross-section task and mediated the correlation between spatial ability and performance. These findings suggest that interactive computer visualisations can aid performance on spatial inference tasks, but that they do so only for a subset of individuals who can discover how to best use the additional information that they provide. Copyright © 2007 John Wiley & Sons, Ltd.

The term 'visualization' is used to refer to both internal mental representations and external displays. Internal spatial visualisation ability can be interpreted as the ability to mentally store and manipulate visual–spatial representations in the mind (Hegarty & Waller, 2005). External visualisations are visual–spatial displays that occur in the world and comprise both static images, such as drawings, graphs, charts and diagrams, and dynamic representations, such as animations. Both forms of visualisation play important roles in scientific and mathematical problem solving (Ferguson, 1977; Miller, 1986). However, science students often have difficulty with both internal visualisation processes and interpretation of external visualisations. For example, studies in the domains of mathematics (Lord, 1985), earth sciences (Eley, 1981; Kali & Orion, 1996; Orion & Ben Chaim, 1997), biology (Russell-Gebbett, 1985), engineering (Gerson, Sorby, Wysocki, & Baartmans, 2001; Hsi, Linn, & Bell, 1997) and medicine (Florance, 2002; Garg, 2001) have pointed to limitations in students' visual–spatial abilities and the need to improve spatial thinking, which includes comprehension, reasoning and problem solving with displays of visual–spatial information.

Concurrent with the recognised need for improvement in spatial thinking is the growing availability of dynamic, interactive, three-dimensional (3-D) computer visualisations (Card, MacKinlay, & Shneiderman, 1999; Florance, 2002). By displaying multiple views of an object, dynamic displays can help learners understand the internal structure of an object. Interactivity adds another dimension of user control, allowing users to advance or

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pause a visualisation at a self-controlled rate, alter the order in which information is viewed or alter parameters in a simulation. The present research was motivated by intersecting developments in scientific education and computer visualisation: the call from the science education community for expanded spatial visualisation training, and the rapid growth of 3-D computer visualisations that may have the potential to augment spatial understanding.

One specific skill that is central to visual–spatial thinking in science, engineering and medicine is the ability to infer and interpret cross-sections of 3-D objects. A cross section is the plane, or flat surface, that results when a 3-dimensional object is cut by a 2-dimensional plane, that is, a 2-D slice of a 3-D object. Russell-Gebbett (1985) identified two discrete skills that were used by secondary school pupils to understand 3-D structures in biology: the abstraction of sectional shapes, and an appreciation of the spatial relationships of internal parts of a 3-D structure seen in different sectional plans. The ability to imagine cross sections, including the internal structure of 3-D forms is also central to geology, where it has been referred to as 'visual penetration ability' (Kali & Orion, 1996; Orion & Ben Chaim, 1997) and to engineering drawing (Gerson et al., 2001; Hsi et al., 1997). In medicine, the ability to infer and comprehend cross sections is central to learning anatomy and using medical images such as X-ray and magnetic resonance images (Hegarty, Keehner, Cohen, Montello, & Lippa, 2007).

In this paper, we examine the contributions of spatial ability and the use of external animations, to performance on a task that requires imagining and drawing the cross section of an imaginary object. The stimulus figure was an egg-shaped object with a transparent exterior that revealed an internal network of duct-like structures (see Figure 1, left). A novel fictitious figure was used so that participants would not be influenced by prior knowledge of the structure. In consideration of the importance of visualisation in biology and medicine, the ducts of the object were designed to resemble in shape and complexity an anatomical object such as the biliary ducts of the human liver. In the experimental trials, a superimposed vertical or horizontal line on the printed images indicated where participants should imagine the structure had been sliced. An arrow indicated the orientation from which the participants were to imagine the cross section. In other words, the participants' task was to imagine what the cross section would look like from the viewpoint of the arrow and to draw the cross section that would result. While performing the task, participants had unlimited access to two dynamic animations of the stimulus object, which allowed them to

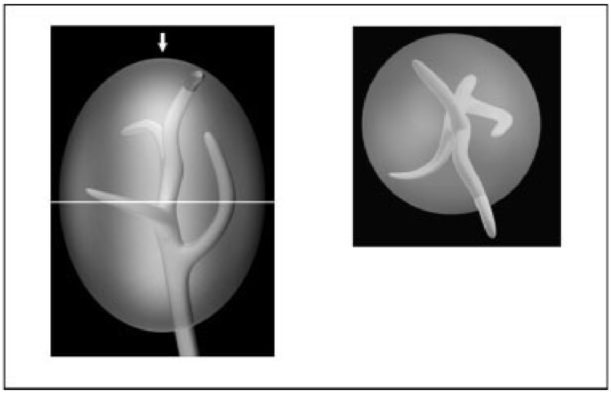

Figure 1. Stimulus (left) and arrow view (right) for a stimulus trial

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rotate the stimulus object 360° around its vertical and horizontal axes, respectively. Both animations were accessible to participants at all times, however, they were sized to fill the entire area of the computer monitor, so that only one was visible at a time.

An informal task analysis suggests that there are a number of cognitive operations that participants need to accomplish (not necessarily in the following order) to complete the task. One step is to encode the spatial characteristics of the stimulus object, such as the outer shape, the location and axis of the line and the spatial relationships among the ducts. Another step is to assume the perspective of the arrow, which was always perpendicular to the superimposed line (see the example in Figure 1, left). We hypothesised that participants could use one of three strategies to assume this perspective: they could mentally rotate an internal representation of the object, they could mentally change their perspective with respect to their internal representation of the object or they could rotate one of the external animations of the stimulus object to the viewing perspective indicated by the arrow. We refer to the viewing perspective indicated by the arrow as the 'arrow view' (Figure 1, right). A third step in performing this task is to mentally imagine slicing the object and removing the section of the object between the viewer and the cross-sectional plane. Final steps are to infer and draw the configuration of ducts that would be visible in the resulting cross section.

Given that the task involved encoding, storing and mentally manipulating spatial representations, our first hypothesis was that spatial abilities would be correlated with performance in this task. Specifically, because our informal task analysis suggested that either mental rotation or perspective taking processes could be used to assume the perspective of the arrow, we predicted that mental rotation and perspective taking abilities would predict performance.

Our second hypothesis was that people who used the external visualisations (interactive animations) more often would perform better on this task. There are at least two ways in which these animations might improve performance. First, in the absence of stereoscopic displays, which represent spatial depth through binocular parallax, standard computer monitors are capable of representing only pictorial depth cues to indicate the 3-D structure of an object. By rotating the external visualisation, participants also receive depth cues through motion parallax, which can be defined as the process of perceiving depth from the difference in the speed of movement for near and far objects. This additional depth information, which can be gained by rotating the object in any direction, may aid in constructing a high-quality internal representation of the 3-D structure, which could then be mentally processed to infer a cross section. Second, by rotating the external visualisation to the arrow view, a participant would be relieved of the need to mentally rotate the object or mentally shift perspective with respect to the object. Thus one of the mental steps (assuming the perspective of the arrow) would be offloaded on the external representation rather than performed internally. This is an example of what Kirsh and Maglio (1994) refer to as an epistemic action, that is, a physical action (in this case, a rotation of the external visualisation) performed 'to uncover information that is hidden or hard to compute mentally' (p. 513).

Although the external animation has the potential to aid performance in these ways, previous studies have indicated that not all individuals are able to use interactive animations effectively (Hegarty, 2004; Rieber, Tzeng, & Tribble, 2004). For example, they do not use the interactive controls, or use interactivity to attend to superficial rather than thematically relevant information (Lowe, 2004). In a review of the interactivity literature Betrancourt (2005) hypothesised that only more experienced learners benefit from certain types of interactivity. An important goal of this study was to begin to examine how people use interactive animations in a spatial inference task and how their use of interactive animations is related to task performance. Based on previous research, we expected individual differences in how effectively people used the external visualisations, and hypothesised that these individual differences would be correlated with task performance.

METHOD

Participants

Thirty undergraduate students recruited from the subject pool of the Psychology Department at the University of California, Santa Barbara, participated in return for course credit.

Materials

Spatial ability tests

Participants completed the Vandenberg Mental Rotation Test (Vandenberg & Kuse, 1978) and a modified version of Guay's Visualization of Views Test (Eliot & Smith, 1983). In the Vandenberg Mental Rotation Test, participants view a depiction of a 3-D target figure and four test figures. Their task is to determine which of the test figures are rotations of the target figure, as quickly and accurately as possible. The maximum possible score is 80. The Visualization of Views Test (VV) measures the participant's ability to visualise an unfamiliar 3-D object from an imagined perspective. The criterion figure is a line drawing of a transparent cube with a small block floating in its centre. The participant must identify the corner of the cube from which a given alternate view of the small block would be visible. The maximum possible score is 24.

Drawing trials

Participants completed 12 cross section drawing trials. The stimulus for each trial was a colour image, printed on an 8 × 11-inch sheet of paper that showed a perspective view of the stimulus object (see Figure 1, left). The image was created in 3D Studio Max and Photoshop. A horizontal or vertical line was superimposed on the figure at a different location in each trial. An arrow that was perpendicular to the superimposed line pointed to the figure. Printed instructions directed the participant to imagine that the stimulus figure was sliced at the superimposed line, and to draw the cross section that would result if the object were viewed from the perspective of the arrow. A blank space was provided for the drawing next to each stimulus figure.

Interactive animations

There were two animations of the stimulus object, which were constructed in 3D Studio Max and displayed in a Quicktime viewer. One displayed a 360° rotation of the figure around its vertical axis; the second showed a 360° rotation of the figure around its horizontal axis. Both animations were accessible to participants at all times, but the animations were sized to cover the whole computer screen, so that only one was visible at a time. The participants were free to advance or reverse the animations to view the stimulus object rotating at a constant rate with 'forward' and 'backward' buttons, positioned below the animation, or could advance or reverse the animations at their own pace and

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stop them at any view of the object using a slider bar, which was positioned horizontally for both animations.

Procedure

Participants were tested individually. The experimenter first explained what a cross section is and illustrated this explanation by showing them an example of a cross-sectional diagram and a small clay object that was sliced down the centre to reveal a cross section. Then she introduced them to the stimulus object and explained their task, showing the participant a diagram of a cross section that would result from a sample trial. After explaining that the two external animations would be available at all times, the experimenter demonstrated how to advance, reverse, pause and control the speed of the animations with forward and backward buttons and the slider bar. Participants were reminded that they would be videotaped and were asked to 'think aloud' as they performed the task.[1] Each participant was then given a test booklet and completed a sample item before completing the 12 experimental trials at his or her own pace. Finally, the two spatial ability tests were administered.

Scoring

Figure 2 shows the correct cross section (above) and examples of three participants' drawings (below) for the sample item in Figure 1. Participants' drawings were assessed for spatial understanding using four standardised criteria. For each criterion, three coders together examined the range of responses across participants and trials, and developed a passing criterion. A score of 1 was allocated if the drawing passed, 0 if it failed.

Number of ducts

We scored whether the drawing of the cross section showed the correct number of ducts, which was either one, two or three on different trials. All three participant drawings shown in Figure 2 passed on the number of ducts criterion.

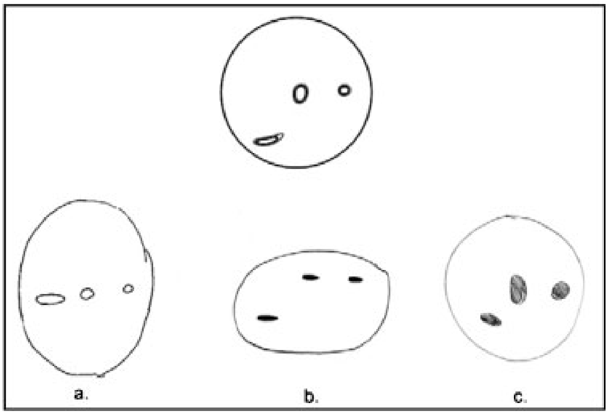

Figure 2. Correct answer (above) and three participant drawings (below) of the cross section of the trial shown in Figure 1

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[1] Several of the participants found it difficult to think aloud while performing the task, as is not unusual for spatial tasks, so we did not analyse the protocols systematically in this experiment.

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Outer shape

We scored the outer shape of the cross section by measuring the maximal width and height of the drawing and calculating the width-to-height ratio. The correct ratio of width to height for the vertical slices (oval cross section) was 0.74, with a permissible range from 0.54 to 0.94. The correct ratio for horizontal slices (circular cross section) was 1.00, with a permissible range from 0.83 to 1.20. In Figure 2, drawing c was the only drawing to pass on the outer shape criterion.

Duct angles

We measured the spatial relationships between the ducts on all the cross sections containing more than one duct. Scorers measured the angles formed by connecting the centres of the ducts in each drawing. For cross sections containing two ducts, a line was drawn connecting the ducts and its deviation from a horizontal line was measured. If the difference between this angle and the correct angle did not exceed 20°, a pass was awarded. For three-duct cross sections, lines were drawn connecting the three ducts, the three resulting angles were measured, and for each the error was calculated as the difference between the correct angle and the drawn angle. These were summed, and if the total error did not exceed 60° (average of 20°), a pass was awarded. If the wrong number of ducts was drawn, a score of 0 was recorded for this measure. In Figure 2, drawings b and c passed on the duct angles criterion.

Duct positions

Finally, we assessed the spatial relations between the ducts and the outer contour of the cross section. A pass was awarded if the position of a drawn duct differed by no more than one tenth of the drawing's width or height from the correct position. All the ducts in a drawing had to pass in order for a point to be assigned for a given trial. If the wrong number of ducts was drawn, a score of 0 was recorded for this measure. In Figure 2, only drawing c passed on the duct position measure.

In a sample of 180 trials, inter-rater reliability across two scorers was 97.3% for the number of ducts measure, 91.6% for the outer shape measure, 95% for the duct angles measure and 91.6% for the duct positions measure.

Use of animation

The video tapes were coded on a trial-by-trial basis for two measures of animation use. The first measure, *stimulus rotation*, assessed whether the participant ever rotated either the horizontal or vertical animation with the slider bar or the forward or backward button on a given trial. The second measure, *observation of arrow view*, was a measure of whether the participants stopped the animation at the perspective of the arrow for each trial. Participants were coded as having observed the arrow view on a trial if they looked at a view of the object that was within 20° of the arrow view for at least 2 consecutive seconds. This could occur either because they rotated the animation to that view in the course of that trial, or because the arrow view was visible on the screen from a previous trial. Two raters independently coded 120 trials and agreed 100% on the stimulus rotation measure and 92.5% on the observation of arrow view measure.

Table 1. Descriptive statistics for spatial ability tests, measures of drawing performance and measures of animation use ($N = 30$)

	M	SD	Range
Spatial ability test scores			
Mental rotation	34.5	16.5	6.0–64.0
Visualisation of Views	10.6	7.1	−1.7–24.0
Drawing measures (proportion correct)			
Number of ducts	0.94	0.08	0.73–1.00
Outside shape	0.69	0.32	0.09–1.00
Duct angles	0.58	0.24	0.13–1.00
Relative position	0.41	0.22	0.00–0.82
Proportion of trials on which animation was used			
Stimulus rotation	0.66	0.39	0.00–1.00
Observation of arrow view	0.60	0.39	0.00–1.00

RESULTS

Drawing performance

Descriptive statistics for the spatial ability tests and drawing measures are given in Table 1.[2] Participants' mean performance (proportion correct) on the number of ducts measure was near-ceiling (0.94) and had low variance (0.08), while performance on the remaining three measures was considerably lower and varied across participants (see Table 1).

Correlations between the spatial ability measures, drawing measures and animation use are shown in Table 2. Three of the drawing measures (outside shape, duct angles and relative position) were highly correlated with each other. For this reason, the measures were combined into a single 'Drawing Accuracy' measure, which was computed by averaging the proportion correct for outside shape, duct angles and relative position (see Table 2 for its correlations with other variables). Number of ducts was not significantly correlated with the other drawing measures, reflecting its low variance, due to a ceiling effect. This measure was not included in subsequent analyses.

Animation use

Descriptive statistics for the proportion of trials on which participants rotated the animations and observed the arrow view are shown in Table 1. These measures were highly correlated (0.94, $p < 0.001$) and in general, when participants rotated an animation on a given trial, they tended to also observe the arrow view. On only 7% of trials participants rotated the animation but did not observe the arrow view and on only 2% of trials participants observed the arrow view but did not rotate the animation. The distributions of both measures were bimodal such that participants either used the animation on most of the trials or on few or no trials. We created a new dichotomous variable, 'Animation Use', which classified each participant as either a frequent or an infrequent user of animations. Nineteen participants were frequent users of the animation (rotated an animation on a minimum of nine trials, $M = 10.32$, $SD = 0.89$) and observed the arrow view on eight or

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[2] One drawing trial was not scored because the cross section cut the internal ducts to make a shape was difficult to draw and the variability on this trial was not captured by our coding system.

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Table 2. Correlations among the spatial ability measures, drawing measures and measures of animation use ($N = 30$)

	1	2	3	4	5	6	7	8	9
1 Mental rotation	—	—	—	—	—	—	—	—	—
2 Visualisation of views	0.32	—	—	—	—	—	—	—	—
3 Number of ducts	0.07	0.48^{**}	—	—	—	—	—	—	—
4 Outside shape	0.31	0.33	−0.07	—	—	—	—	—	—
5 Duct angle	0.28	0.63^{**}	0.29	0.46^{*}	—	—	—	—	—
6 Relative position	0.43^{*}	0.62^{**}	0.17	0.50^{**}	0.89^{**}	—	—	—	—
7 Drawing accuracy	0.39^{*}	0.59^{**}	0.13	0.81^{**}	0.88^{**}	0.89^{**}	—	—	—
8 Stimulus rotation	0.52^{**}	0.61^{**}	0.15	0.56^{**}	0.72^{**}	0.79^{**}	0.79^{**}	—	—
9 Obs. of arrow view	0.56^{**}	0.66^{**}	0.15	0.59^{**}	0.73^{**}	0.79^{**}	0.81^{**}	0.94^{**}	—
10 Animation use	0.53^{**}	0.59^{**}	0.10	0.66^{**}	0.73^{**}	0.76^{**}	0.84^{**}	0.95^{**}	0.94^{**}

$^{*}p < 0.05$ (two tailed).
$^{**}p < 0.01$ (two tailed).

more of the trials ($M = 9.7$, $SD = 1.2$). The other 11 participants were infrequent users of animation (rotated an animation on five or fewer trials, $M = 2.1$, $SD = 1.9$) and observed the arrow view on six or fewer trials ($M = 1.5$, $SD = 1.9$). Table 2 shows the correlations of animation use with the other variables of interest.

Predictors of performance

We hypothesised that performance on the cross-section task would be correlated with measures of spatial ability. Consistent with this prediction, the zero-order correlations of mental rotation (0.39), and visualisation of views (0.59) with drawing accuracy were significant. Our hypothesis that use of the animation would be positively related to performance was also supported by a very high correlation of animation use with drawing accuracy (0.84).

Animation use was significantly correlated with the spatial ability measures. This raises the question of whether spatial ability and use of animation make independent contributions to predicting drawing accuracy, or whether the effects of spatial ability are mediated by the use of animation. To investigate these questions we conducted a series of regression analyses following guidelines provided by Baron and Kenny (1986). For these analyses we used Visualisation of Views as the measure of spatial ability because it was most highly correlated with drawing accuracy.[3]

Figure 3 summarises the results of the mediation analyses. In the first equation, we regressed drawing accuracy on Visualisation of Views and found a significant relationship ($\beta = 0.59$, $p < 0.001$). In the second equation we regressed use of animation (our proposed mediator) on Visualisation of Views and again the relationship was significant ($\beta = 0.59$, $p < 0.001$). In the final equation we regressed drawing accuracy on both Visualisation of Views and use of animation. In this equation, the association between use of animation and drawing accuracy was highly significant ($\beta = 0.75$, $p < 0.001$), but the contribution of Visualisation of Views was reduced and not statistically significant ($\beta = 0.15$, n.s.). Taken

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[3] A regression analysis also indicated that mental rotation did not significantly predict drawing accuracy independently of the Visualisation of Views measure.

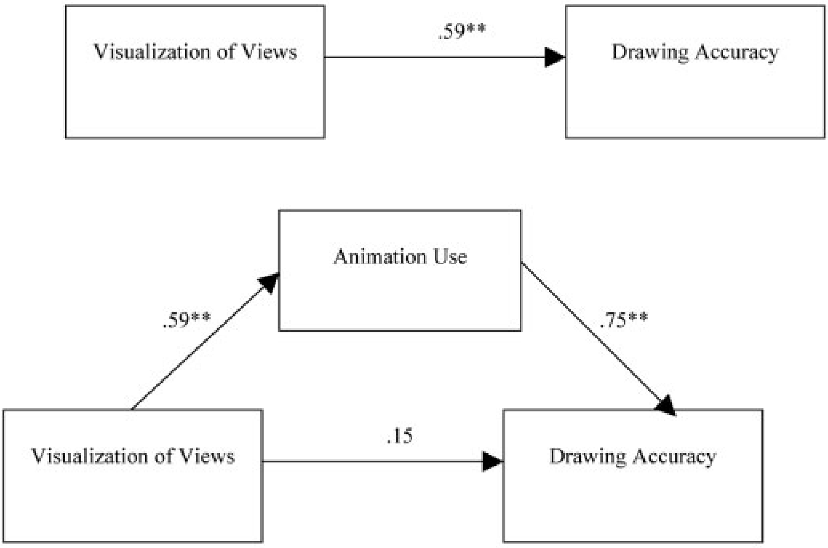

Figure 3. Mediation analysis path diagram

together, these findings suggest that use of animation mediates the relationship between spatial ability and drawing accuracy.

DISCUSSION

The results of this study support our hypotheses that both spatial ability and use of external visualisations are related to performance in inferring cross sections. Consistent with previous studies (Lowe, 2004; Rieber et al., 2004) there were large individual differences in how much and how effectively people used the external visualisation. A novel result of this study is that effective use of these visualisations is related to spatial ability.

One step in the cross-section task is to assume the perspective of the arrow and this can be accomplished either by internal visualisation processes (mental rotation or perspective taking) or by rotating the external visualisation. Participants with good internal visualisation abilities were more likely to use the external visualisation (i.e. perform an epistemic action, Kirsh & Maglio, 1994), whereas those with poorer abilities relied more on internal visualisation. Thus, there is no evidence in this study that people use external visualisations more to compensate for poor internal visualisation abilities and in fact the data suggest that productive use of external visualisations may depend on good internal visualisation abilities.

Use of the external visualisation mediated the relationship between spatial ability and performance in this study, raising the question of whether spatial ability would predict performance on the cross-section task if a non-interactive animation or no animation were used. In other studies (Hegarty et al., 2007) we have found that spatial ability does predict performance in these situations, suggesting that spatial ability is related to the internal computations to be performed in inferring cross sections, and not just to the control of external visualisations. Furthermore, in recent studies (Hegarty, Keehner, Cohen,

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Khooshabeh, & Montello, 2006) we have observed a correlation between spatial ability and a multiple-choice version of this task that involves recognising the correct cross section, suggesting that drawing ability is not the limiting factor.

The visualisations in this experiment gave the participants two degrees of freedom to rotate the objects around the horizontal and vertical axes. Our conclusions are specific to this type of visualisation, and further research is required to examine how these results generalise to other interfaces, such as those allowing rotation in three dimensions. In related studies with such an interface (Keehner, Hegarty, Cohen, Khooshabeh, & Montello, 2006), spatial ability did not predict effective use of the interface, although both spatial ability and using the interface effectively (to observe the arrow view) predicted task performance.

Our measures of animation use in this study (stimulus rotation and observation of the arrow view) were rudimentary, although they captured large variance between subjects. Future research should focus on more finely characterising the strategic differences between low-and-high spatial individuals. A preliminary protocol study (Cohen, 2005) indicated that low-spatial participants have difficulty mapping the 2-dimensional representation in the stimulus trials to the 3-D interactive visualisation on the computer screen, and tend to get disoriented once they rotate the animation.

In conclusion, this study was motivated by both the call from the science and medical education communities for expanded visualisation training and increased availability of 3-D computer visualisations. Our findings suggest that interactive computer visualisations may augment performance on spatial inference tasks, but that not all individuals spontaneously discover how to best use the additional information that they provide. Merely providing individuals with these external aids does not compensate for limited internal visualisation abilities. More research is needed to better understand strategy differences between successful and less successful students on this task so that we can discover either how to design visualisations to address the needs of low-spatial individuals or how to instruct these individuals to use external visualisations more effectively.

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