

Interface Design and Spatial Cognition: A Case of Virtual Molecule Manipulation

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Abstract

Virtual models are a common instructional tool used in chemistry education to help students learn about the 3D structure of molecules. The present study examined effects of two interface design features on participant performance during a molecule orientation task. The features examined were 1) colocation of the visual and haptic workspace and 2) stereoscopic viewing. The results indicate that colocating the interface increased participant accuracy, while providing stereo did not. Neither factor affected response time. The effects of colocation were also reflected in subjective ratings of task demand measured by the NASA-TLX. Spatial ability was predictive of task performance but did not interact with interface effects. The findings are discussed in the context of spatial cognition and interface design for manipulating virtual objects.

Keywords: spatial cognition; interface; virtual; rotation; stereoscopic; colocation; organic chemistry

Computer-based virtual models are becoming an increasingly common instructional medium in science, technology, engineering, and mathematics (STEM) education (Trindade, Fiolhais & Almeida, 2002). Virtual learning environments have shown promise in fostering meaningful learning, but virtual models vary considerably in the perceptual cues and interfaces that they provide so there is still much to be understood regarding how to best design and implement these technologies. For example, current stereoscopic displays are more expensive and less available, so it is important to know whether they provide a benefit to performance and learning outcomes, or whether monoscopic displays are as effective.

The present study aims to understand the relative value of two factors on which virtual displays vary, (1) colocating the hand-held interface and the displayed virtual image (colocation), and (2) providing stereoscopic 3D viewing (stereo) for a representation matching task in organic chemistry. Stull, Barrett, & Hegarty (2012), found participants performed this task with greater efficiency using a virtual model system (with stereoscopic display and colocation of visual and haptic workspaces) than when using standard concrete models. Given this efficiency advantage, a goal of this study is to investigate the relative importance of providing stereo and colocation during a virtual object manipulation task.

Klatzky, Wu, & Stetten (2008) suggest that more perceptually mediated interfaces allow for better performance over cognitively mediated interfaces. Perceptually mediated interfaces decrease demand on spatial working memory, thereby freeing up cognitive resources to allocate to performance or learning. If stereo and colocation increase perceptual mediation, decrease spatial cognitive load, and allow for additional cognitive resources to be devoted to performance, then participants should show faster and more accurate performance when these cues are provided.

Stereo and Colocation Technology

Both stereo and colocation technologies have been shown to increase speed and accuracy in virtual object manipulation tasks (Ware & Rose, 1999, Arsenault & Ware, 2004, Klatzky et al., 2008), however some studies have shown no significant effect of stereo (Khooshabeh & Hegarty, 2010) or colocation (Liere, 2005). It is important to note that the majority of studies investigating performance with these technologies have used object translation tasks, rather than a rotation task as in the current study. In general, we should be cautious in generalizing specific interface design effects across various tasks, as different perceptual cues may be important for supporting rotation and translation.

To our knowledge, no study has investigated the effects of varying both stereo and colocation during a virtual object rotation task in the same experiment. The results of the present study will help to elucidate the importance of these cues for increasing perceptual mediation and decreasing cognitive load in a task that involves virtual object rotation.

Organic Chemistry as a Test-bed

Organic chemistry is a domain rich in spatial representation; diagrams and models of 3D molecular structures are ubiquitous in instruction as well as in cutting edge research environments. Understanding molecular structure is an essential skill all organic chemists must have in order to learn, research, and communicate their science. Diagrams and models serve as a language of spatial connections and structures and therefore are vital in developing understanding of structures and making advancements in the field (Kozma & Russell, 2005).

Organic chemistry representations serve as an excellent test-bed for studying spatial cognition in virtual environments for these reasons. Virtual models are commonly employed in chemistry education (Barnea & Dori, 2000, Limniou, Roberts & Papadopoulos, 2008) to teach students about the 3D structure of molecules and to introduce them to other representations (diagrams, equations etc.). However, little work has investigated interface design for virtual models in chemistry. One aim of the present study is to inform the design of virtual models for chemistry education, by identifying which visual cues and interface functionality best support usability and learning with these models.

The task used in the present study requires that the participant understand the spatial structure of a 3D molecular model, then manipulate the model in order to match to the orientation of a simultaneously displayed diagram of the same molecule. This task is relevant as it is a commonly employed activity for teaching about molecular structure, and also shares similarities with the virtual object orientation matching tasks used in the human-computer interaction literature. Grounding the study in the real-world domain of organic chemistry allows for simultaneous investigation of applied interface design issues as well as theories of small scale spatial cognition and virtual object manipulation.

In addition to performance measures, we assessed self-reports of usability of the virtual models. We predicted that participants who received stereo and colocation would rate the interfaces as more usable. Given the spatial nature of the task and known sex differences in spatial ability (Voyer, Voyer & Bryden, 1995), we also investigated possible interactions between aspects of the virtual models, spatial ability, and sex. If colocation and stereo displays increase perceptual mediation, we might expect an interaction with spatial ability such that lower spatial ability participants should receive a greater benefit from the additional cues than higher spatial ability participants, who can presumably better handle more cognitively mediated interfaces. We might also expect females to benefit more from the perceptually mediated interface, because they tend to have lower spatial ability (Voyer et al, 1995) and less experience with computers (Waller, 2000).

Virtual Model System

A ‘fishtank’ virtual reality system was constructed to allow for colocated naturalistic manipulation of a virtual molecular model in stereoscopic 3D (Earnst & Banks, 2002). The display was mounted horizontally above the user and faced downward onto a mirror mounted at 45°, which projected the virtual image to the viewer. This configuration allowed the participant to manipulate the input device in the same location as the perceived virtual image of the model, giving an experience similar to direct manipulation of a concrete model. In the displaced condition, the input device

was located to the left and below the image in the natural computer mouse location (15° total displacement). Stereoscopic viewing was provided by Nvidia 3D Vision Wireless Glasses Kit.

The interface was composed of a cylinder that was roughly the same dimensions as the virtual models, and consisted of two halves that freely rotated about the long axis of the interface. One half contained a 3-degree of freedom motion sensor to track yaw, pitch, and roll of the interface, and was used to control global rotations of the virtual models. The opposite half was attached via an optical encoder that tracked twisting rotations of the interface halves, and was used to control local rotations of a bond within the molecule itself (as was necessary on some of the experimental trials). Please refer to Stull, Barrett & Hegarty (2012) for a more detailed description of the system design.

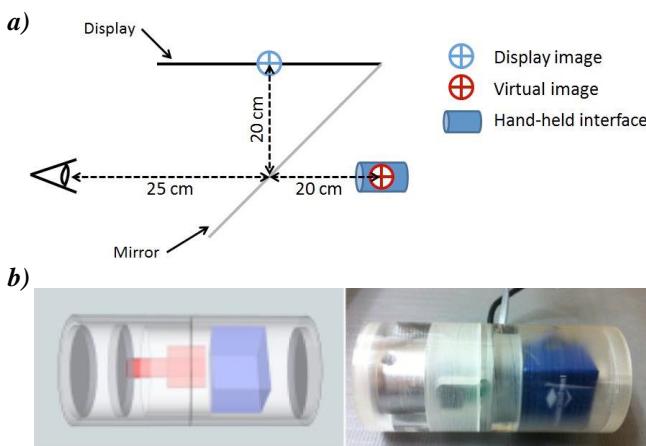


Figure 1: *a*) The hand-held interface workspace was colocated with the displayed virtual image. *b*) The motion sensor is depicted in blue, and the optical encoder is depicted in red. The cords for the two devices emerged at the junction between the two halves.

Method

Design

The study had a two (colocation vs. displaced) by two (stereo vs. mono) between subjects design. Dependent variables include accuracy as measured by angular error and response time. Subjective experience ratings, spatial ability, and computer use were also measured.

Participants

One hundred twenty college students (65 Female) (age: $M = 18.7$, $SD = 1.8$) from the psychology subject pool at a research university participated in the study in return for course credit. None of the participants had studied organic chemistry. All participants had normal, or corrected to normal vision. Participants were randomly assigned to each condition.

Materials

The study materials included an informed consent sheet, a video tutorial, a sheet with descriptions of the task and diagrams, a set of diagram orientation matching task problems, a measure of task load, a measure of computer beliefs and attitudes, two measures of spatial ability, and a post-task questionnaire.

A 10-minute instructional video explained the conventions of the models and diagrams, how to find and understand important features of the model (e.g., central carbon-carbon bond), how to write the chemical formula for each molecular subgroup (e.g., CH₃ for a methyl group made up of a carbon atom and three hydrogen atoms), the color conventions for the different atoms (e.g., black for carbon, red for oxygen etc.), and how to structurally align the models to each of the three diagram types.

The diagram problems required rotation of the virtual model to match one of two commonly used target diagram types, dash-wedge (side-view) and Newman (end-view). There were 24 problems total, half with dash-wedge target diagrams and half with Newman target diagrams. The starting orientation of the model was such that it maximized the global angular distance to each of the target diagrams. Half of the trials involved a conformation change (local rotation) of the molecular model (i.e., changing the spatial configuration of substituents by rotating the bond between the molecule's two chiral carbons). Six different molecules were used in the 24 trial problems; and were systematically varied with the target diagram type, and local rotation trials. All participants received the trials in the same order, in which two consecutive trials never showed the same target diagram or molecule.

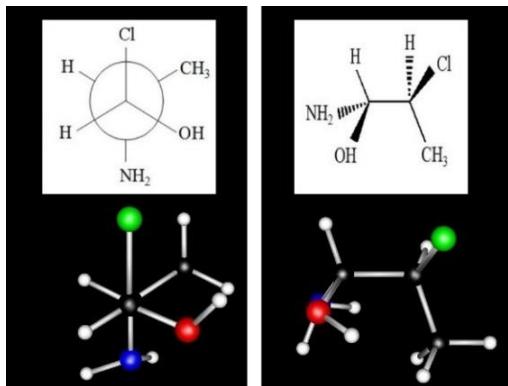


Figure 2: Participants manipulated the 3D molecular model to match the orientation depicted by either a Newman (left) or Dash-Wedge (right) diagram.

Items from the NASA Task Load Index (TLX) (Hart & Staveland, 1988) were administered to assess participants' subjective experience of the task with regard to six criteria: mental demand, physical demand, temporal demand, own performance, effort, and frustration. Participants rated each

of these criteria on a scale from 0 to 100 with 0 being the lowest and 100 being the highest rating.

Participants were administered two tests of spatial ability, a mental rotation test (MRT) (Vandenburg & Kuse, 1978), and a three dimensional perspective taking test, Visualization of Viewpoints (VoV) (Guay & McDaniels, 1976).

Items from Waller's (2000) computer use questionnaire were administered to assess participants' attitudes and experience with computers. Participants rated 10 statements on a scale of 1 (completely disagree) through 7 (completely agree).

Results

The following results include 108 participants (56 female). Data from 12 students were excluded from the analyses as they had much lower accuracy (angular errors of >30°) suggesting they did not understand the task or were unmotivated. The four interface condition groups had approximately equal numbers of males and females. Response times that were greater than 2.5 standard deviations from a participant's mean response time were replaced with their mean response time. The groups did not significantly differ on the MRT, $F(3, 104) = 0.8, p = .56$, VoV, $F(3, 104) = 1.7, p = .17$, computer experience, $F(3, 104) = 0.43, p = .73$, or attitudes toward computers, $F(3, 104) = 1.0, p = .42$.

The mean angular error for the different experimental groups is shown in Figure 3. Overall, participants had an average angular error of 13.7° ($SD = 6.6$). A significant effect of colocation was found on error, $F(1, 104) = 6.6, p = .01, \eta_p^2 = .06$. Marginal means showed that participants provided with the colocated interface had a lower average angular error (i.e., greater accuracy) of 12.1° ($SD = 5.7$), than those using the displaced interface 15.4° ($SD = 7.1$). No significant effect of stereo was observed, $F(1, 104) = 0.6, p = .46$. There was no observed interaction between colocation and stereo $F(1, 104) = 2.5, p = .12$.

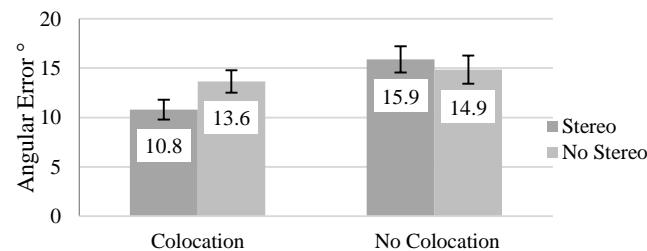


Figure 3: Effects of providing stereo and colocation on participant accuracy ($M \pm SE$).

Overall, participants had an average response time of 33.8s ($SD = 15.2$). No significant effect of colocation was found on response time, $F(1, 104) = 1.5, p = .22$. Also, no significant effect of stereo was observed, $F(1, 104) = 1.2, p$

$= .28$. There was no observed interaction between colocation and stereo, $F(1, 104) = 0.6, p = .43$.

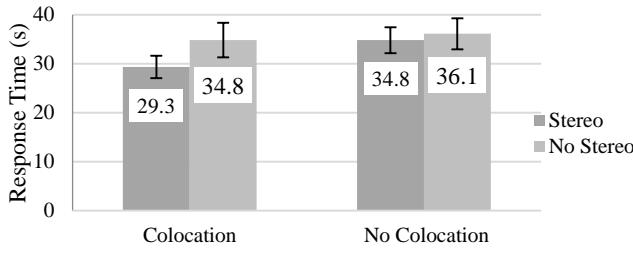


Figure 4: Effects of providing stereo and colocation on participant response time ($M \pm SE$).

NASA-TLX ratings are shown in Table 1. On average, participants provided with a colocated interface rated their experience as having significantly less physical demand and frustration than those with the displaced interface. Further, participants with colocated interfaces rated their own performance to be significantly greater than those with displaced interfaces. No main effects of stereo were found on any of the six task demand ratings.

Significant interactions between stereo and colocation were observed on ratings of effort, $F(1, 104) = 4.3, p = .04, \eta_p^2 = .04$, and frustration, $F(1, 104) = 8.3, p = .005 \eta_p^2 = .06$. When colocation was provided, participants using stereoscopic displays reported less task effort ($M = 58.1, SE = 4.6$) than participants using monoscopic displays ($M = 72.3, SE = 4.8$). Further, when provided stereo, participants using colocated interfaces reported less frustration ($M = 19.4, SE = 5.1$) than those using displaced interfaces ($M = 45.6, SE = 5.3$).

Table 1: Effect of stereo and colocation on NASA-TLX ratings.

Task Demand	Colocated	Displaced	ANOVA			
	$M (SE)$	$M (SE)$	df	F	p	η_p^2
Mental	48.1 (3.3)	53.8 (3.3)	104	1.5	.23	—
Physical	24.4 (3.3)	34.2 (3.4)	104	4.2	.04	.04
Temporal	44.6 (3.1)	46.9 (3.1)	104	0.3	.60	—
Performance	82.2 (2.3)	75.2 (2.3)	104	4.6	.03	.04
Effort	65.2 (3.3)	65.7 (3.4)	104	0.0	.92	—
Frustration	25.4 (3.7)	36.5 (3.8)	104	4.3	.04	.04
	Stereo	Mono				
Mental	48.9 (3.2)	52.9 (3.4)	104	0.7	.40	—
Physical	30.9 (3.3)	27.8 (3.4)	104	0.4	.52	—
Temporal	49.5 (3.1)	42.1 (3.2)	104	2.9	.09	—
Performance	76.7 (2.3)	80.8 (2.4)	104	1.5	.22	—
Effort	63.3 (3.3)	67.6 (3.4)	104	0.8	.36	—
Frustration	32.6 (3.7)	29.2 (3.8)	104	0.4	.52	—

* $p < .05$; N = 108

Table 2: Correlations between dependent measures, spatial ability, and computer use.

	RT	Ang. Error	MRT	VoV	Comp. Att.	Comp. Exp.
RT	1	—	—	—	—	—
Ang. Error	.36**	1	—	—	—	—
MRT	-.25*	-.25**	1	—	—	—
VoV	-.32**	-.36**	.45**	1	—	—
Comp. Att.	-.17	-.07	.30**	.34**	1	—
Comp. Exp.	-.221*	-.13	.30**	.31**	.59**	1

* $p < .05$, ** $p < .01$, two-tailed; N = 108

As shown in Table 2, MRT scores showed small but significant correlations, while VoV scores showed somewhat higher correlations with response time and accuracy. In order to investigate possible interactions between spatial ability and aspects of the interface and display, scores from the MRT and VoV were standardized and averaged to produce a combined spatial ability score. A median split was used to separate high and low spatial ability participants, and was then used as a factor in the analysis. As expected, high spatial ability participants completed the task faster and had greater accuracy than low spatial ability participants $F(1, 100) = 7.9, p = .006, \eta_p^2 = .07$. High spatial ability participants had an average response time of 29.3s ($SD = 12.2$) and low spatial ability participants 38.1s ($SD = 16.6$). For accuracy, high spatial ability participants had a lower average angular error of 11.2° ($SD = 5.6$) than low spatial ability participants 16.2° ($SD = 6.5$), this finding was also significant $F(1, 100) = 13.2, p = <.001, \eta_p^2 = .12$. Interactions of spatial ability with stereo and / or colocation did not reach significance.

Participants' level of experience with computers showed a small significant correlation with accuracy, but no significant correlation with response time. As shown in Table 2, there were moderate correlations between computer attitude and experience with both the MRT and VoV scores. A median-split was used to separate participants into high and low groups for computer attitude and computer experience. When used as a factor in the analysis, there was no main effect of either attitude or experience on performance. Further, there were no significant interactions of computer attitude or experience with stereo and / or colocation.

Overall, males were significantly more accurate than females, $F(1, 106) = 5.1, p = .025, \eta_p^2 = .05$. Males had an average angular error of 12.3° ($SD = 6.6$) and females 15.1° ($SD = 6.3$). Males and females did not significantly differ in response time, $F(1, 106) = 0.5, p = .50$. However, a significant interaction of gender with colocation is evident in response time, $F(1, 104) = 5.0, p = .028, \eta_p^2 = .05$.

Pairwise analysis revealed that female participants performed significantly faster with a colocated interface ($M = 29.9$ s, $SE = 2.8$) than with a displaced interface ($M = 39.8$ s, $SE = 2.8$), $F(1, 104) = 6.2$, $p = .014$, $\eta_p^2 = .06$. Response times for males were not affected by colocation, $F(1, 104) = 0.4$, $p = .49$. There were no other significant interactions with gender.

Discussion

The main purpose of this study was to examine the importance of providing stereoscopic 3D viewing and colocation of the haptic interface and virtual image during a virtual object orientation task using molecular models. The results demonstrate that providing colocation had a small but significant impact on accuracy. The experiment failed to demonstrate an effect of stereo on accuracy. The results failed to show an effect of colocation or stereo on task completion speed. Overall, these findings suggest that colocation of haptic and visual information enabled perceptual mediation of the task to some degree, whereas stereo did not significantly increase perceptual mediation or decrease cognitive load for this particular task.

Our results can be compared with previous studies investigating the effect of colocation on virtual object rotation. Ware and Rose (1999) found that colocation led to 35% faster performance during an object rotation task, however no effect on accuracy was found. In a later study, Ware and Arsenault (2006) found that colocation led to faster response times, however they did not have a measure of accuracy because trials were automatically terminated when the manipulated object was within 5° of the target orientation. Other studies investigating effects of colocation are difficult to compare with the present study; the majority of tasks used involve object translation rather than pure object rotation, as in our task.

The findings of the present study demonstrate an accuracy advantage, rather than the speed advantages demonstrated in the previous studies. In regard to the Ware and Rose (1999) result, it is important to note the authors' task involved repeatedly rotating a single simple shape and did not require any local manipulation of the object, as in our task. It is possible that when task demands are greater, providing colocation benefits accuracy more than response time. In regard to Ware and Arsenault (2006), the accuracy advantage from colocation found in the present study would translate into a response time benefit had the trials required a minimum angular error for completion; thus it is likely that the findings are complementary. Despite the relatively small effect on accuracy, this study adds to the body of literature demonstrating a performance benefit from colocating visual and haptic workspaces for virtual object rotation tasks. Further, this study shows that when rotating different complex structures to match a given orientation, providing colocation of haptic and visual information may benefit precision more than speed.

Numerous studies have demonstrated performance advantages from providing stereoscopic 3D viewing in virtual object manipulation tasks (Ware & Franck, 1996; Hu, Hellen, 2000; Arsenault & Ware, 2004; Liere, Kok, Martens, 2005). However, many of these studies involve virtual object translation tasks, rather than rotation tasks, as in the present study. One must use caution in generalizing effects of interface design on translation tasks to rotation tasks, as the two processes are independent (Wang, MacKenzie, Summers, & Booth, 1998; Ware & Rose, 1999). Other studies comparing stereo and mono displays that involved tasks other than translation often find no beneficial effect of stereoscopic viewing (Hoffmeister, Frank, Cuschieri, & Wade 2001, Kooshabeh & Hegarty, 2010).

Another possible explanation for the null result of providing stereo is that the task had low demand on depth perception. The task used in the present study was purely an object rotation task, the models manipulated were regular structures that rotated around a fixed origin in space, and the task did not require making difficult judgments about relative distances in depth. The tetrahedron structure of the molecules may have allowed for necessary judgments of depth to be made via monocular depth cues such as occlusion, motion, linear perspective, and shadowing. It is possible that the depth perception demands of the task could be supported by monocular cues alone. Despite the growing excitement surrounding 3D stereoscopic displays, performance on certain tasks and applications may not benefit from providing the latest display technology. Future research is needed to elucidate the specific task qualities and learning situations under which providing stereo actually benefits the user.

Results from the NASA-TLX measure of participants' subjective experience were consistent with the performance data, and further demonstrated the importance of providing colocated visual and haptic workspaces and the null effect of viewing the display in stereo. Participants with the colocated interface reported the task to be significantly less physically demanding, less frustrating, and rated their perceived performance higher than participants who used the displaced interface. Participants were more comfortable and confident when the interface was colocated; this provides further evidence that although the performance effects were small, they were meaningful in that they were associated with the perceived task demands of the users. Stereo did not affect ratings of subjective experience, further demonstrating its unimportance for this task.

Males performed the task more accurately than females. An interesting result is that females performed trials about 10 seconds faster when provided with colocation. This result suggests that females have a more difficult time dealing with visual and haptic mismatches, which might be attributed to differences in spatial ability, experience with computers, or both.

This study demonstrated that providing colocated haptic and visual workspaces had a small beneficial impact on accuracy during a virtual object orientation matching task, while providing stereo had no significant effect on accuracy. Further, neither factor affected overall response time. It will be important to examine whether results found on representation matching performance generalize to meaningful learning of the spatial structures. Future studies will investigate how specific interface design features relate to students' ability to understand concepts regarding 3D molecular structure and whether this learning can be maintained and utilized during novel situations in which models are no longer available. In addition to providing basic information regarding the perceptual cues that facilitate virtual object manipulation, this research will inform the design of virtual models for science learning.

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