Eyegaze Analysis of Displays With Combined 2D and 3D Views

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Abstract

Displays combining both 2D and 3D views have been shown to support higher performance on certain visualization tasks. However, it is not clear how best to arrange a combination of 2D and 3D views spatially in a display. In this study, we analyzed the eyegaze strategies of participants using two arrangements of 2D and 3D views to estimate the relative position of objects in a 3D scene.

Our results show that the 3D view was used significantly more often than individual 2D views in both displays, indicating the importance of the 3D view for successful task completion. However, viewing patterns were significantly different between the two displays: transitions through centrally-placed views were always more frequent, and users avoided saccades between views that were far apart. Although the change in viewing strategy did not result in significant performance differences, error analysis indicates that a 3D overview in the center may reduce the number of serious errors compared to a 3D overview placed off to the side.

CR Categories: H.5.2 User Interfaces - Graphical User Interfaces (GUI), Screen Design, Evaluation/Methodology, I.3.3 Picture/Image Generation - Display Algorithms, J. Computer Applications (e.g., CAD, Medical Imaging)

Keywords: visualization, 2D/3D combination display, user study, experiment, eyegaze analysis

1 Introduction

Many tasks, such as estimation of the 2D Euclidean distance between two landmarks in a 3D scene, require a good 3D visualization. We investigate how to provide 3D visualization with minimal effort for such a task, which may arise for example, in surgical planning with 3D medical data.

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IEEE Visualization 2005
October 23-28, Minneapolis, MN, USA
0-7803-9462-3/05/$20.00 ©2005 IEEE.

It is difficult to display 3D spatial data on a 2D monitor in a way that clearly shows both the overall 3D shape of the object and detailed distances between landmarks. Spatial data can be displayed using purely 2D views (slices or orthographic projections from the top / bottom, left / right, or back / front of an object) that provide information about only 2 dimensions, or 3D views (orthographic or perspective projections from a viewpoint off the axes) that provide information about 3D structure. The two view styles are effective for different tasks. For example, 2D views are useful for detailed analysis, navigation, and exact measurements [8][10], whereas 3D views are useful for understanding 3D shape and gauging the spatial relationship between objects [10][17][18].

Because of their respective usages, combining 2D and 3D views into a single display can be valuable for many tasks. For example, Preim *et al.* [6] and Tresens and Kuester [17] suggest using synchronized 2D and 3D views for medical tasks such as surgical planning. In surgical planning, 2D views are useful for selecting specific voxels and performing measurement operations, whereas 3D views are important for understanding the overall spatial relationships between objects and for facilitating discussions among physicians.

In previous work [14][15], we compared displays consisting strictly of 2D or 3D views to displays combining both 2D and 3D views for relative orientation and position estimation tasks that required both precise detail and broad overview. Our experiments demonstrated that providing a combination of both 2D and 3D views can reduce error and increase user satisfaction compared to strict 2D or 3D displays. In this paper, we describe the use of eyegaze tracking to determine what is a visually ergonomic display for 2D and 3D combinations during a relative position estimation task, so that 3D visualization is provided with minimum effort.

These results provide guidance for design of more visually ergonomic displays. The protocols and analytic methods of this work may also serve as a prototype for future evaluations of combined 2D and 3D visualizations.

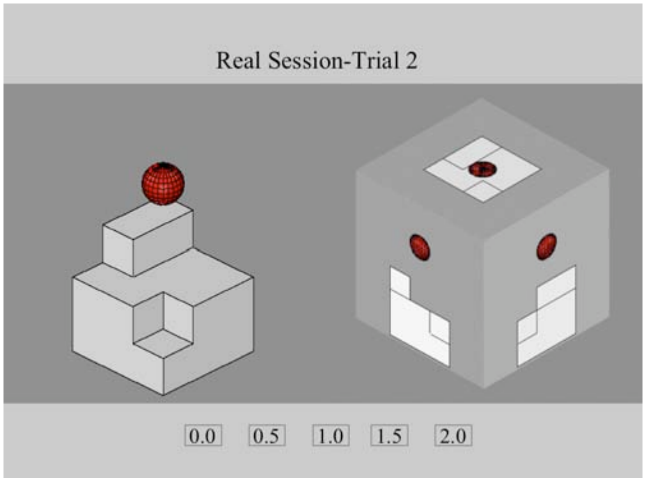
2 Related Work

Several ways of combining 2D and 3D displays have been proposed. A small number of studies have compared performance of users on strict 2D or 3D displays with their performance on 2D/3D combinations.

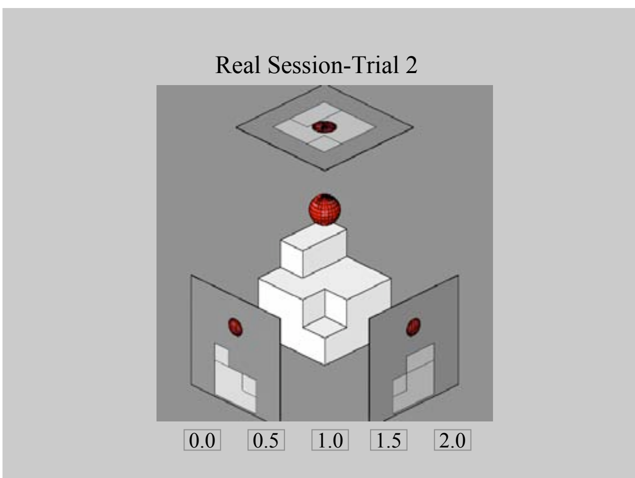
2.1 Displays Combining 2D and 3D Views

The orientation icon (OI) display places 2D and 3D views side-by-side, as shown in Fig. 1 (a). The 3D view "orients" users by indicating the positions of the 2D views relative to the object and each other. Because 2D views are physically separated from the

3D view and could be translated and rotated from their original location, mentally relating 2D and 3D views can be challenging.



(a) Orientation Icon



(b) ExoVis

Fig. 1 Screenshots of (a) Orientation Icon and (b) ExoVis 2D/3D combination displays used in our experiment. The ball is at height 2.0 diameters above the top surface of the block.

The ExoVis display (see Fig. 1 (b)) extends the idea of "interactive shadows" [2] by allowing the display of either 2D slices through the middle of an object or orthographic projections from the side of an object. ExoVis consists of a 3D view in the centre with 2D views surrounding it in close proximity. The 2D views are translated but not rotated from their original orientations.

In earlier work, we showed that mentally relating the 2D and 3D views in ExoVis requires less transformation and cognitive load than orientation icon displays with flat 2D views, but more than a third combination display, the clip plane display [13][16]. The clip plane display shows 2D slices in their exact position within the 3D view (the slice is "in-place"). We compared these three categories of combined 2D/3D displays based upon factors such as flexibility, occlusion, and expected difficulty of view registration [16]. View registration is easier with a clip plane display than with orientation icon or ExoVis. However, because a clip plane hides everything between itself and the viewer, it is generally less useful than other displays and will not be addressed further in this paper.

Other variants of 2D/3D combination displays show a slice of a 3D object surrounded by an outline or semi-transparent surface of the 3D object's outer contour [19], or open the volume like a book [1]. These displays are not considered here because they apply only to 2D slices, not 2D orthographic projections.

2.2 Comparisons of Combined 2D/3D Displays

St. John *et al*. [11] compared strict 2D, strict 3D, and an orientation icon 2D/3D combination display for a 3D route-planning task. Task completion was fastest with the orientation icon display, indicating that combined 2D/3D displays are valuable. However, they did not consider other combined 2D/3D displays such as ExoVis or clip plane displays.

We compared clip plane, orientation icon, and ExoVis 2D/3D combination displays to strict 2D and strict 3D displays for relative position estimation and relative orientation tasks [14][15]. Both the orientation icon and ExoVis displays performed well in terms of time and error, indicating promise for 2D/3D combination displays compared to strict 2D or 3D displays. However, we were unable to show significant differences between these two types of combination displays.

In this paper we compare orientation icon and ExoVis 2D/3D combination displays using a different method: eyegaze tracking of subjects while they perform a relative position task. We hope to observe how display organization affects task strategy, in order to develop efficient displays for such tasks.

2.3 Eyegaze Tracking in Visualization

Eyegaze tracking can be useful in visualization tools for several purposes. The most common use has been as a form of active or passive user input. Examples include:

- Rendering a scene at high resolution near the gaze point and at lower resolution elsewhere (e.g., Levoy and Whitaker [5]).
- Adapting the information content of a system based on perceived user interest (e.g. Qvarfordt and Zhai [7]).
- Using eyegaze tracking as a pointing mechanism (e.g., [3]).

By contrast, we use eyegaze tracking to analyze the effectiveness of different visualization designs. Similar work was done by Spence *et al* [9], who compared several methods of displaying sets of images, using eyegaze tracking to examine the effect of display type on viewing patterns. Our work considers different visualization techniques, tasks, and eyegaze measures than Spence *et al*.

3 METHOD

This experiment compares orientation icon and ExoVis displays for a relative position estimation task. The task and stimuli were similar to our previous work [14][15], but there were differences in the method, most notably the collection of eyetracking data, and a within-subjects rather than a between-subjects design.

3.1 Experiment Design

We used a 3 x 5 (display x ball height) within-subjects design (all participants were tested with all displays and ball heights). We measured time, errors, and subjective ratings of difficulty, and tracked participants' eyegaze during the trials.

3.2 Task & Stimuli

The task was a variation of St. John *et al.*'s relative position estimation task [10]. Participants estimated the empty vertical space (height) between a ball and a block shape (see Fig. 1). The empty space was always 0, 0.5, 1, 1.5, or 2 sub-block sized units.

Scenes were presented as static images on a 17" screen at 1024 x 768 display resolution. Block shapes were generated by removing 2, 5, or 8 cubes from a base shape containing 27 cubes (3 x 3 x 3). Orthographic 2D views were rendered from the top, right, and left. 3D views were also rendered with orthographic projection, to closely emulate St. John *et al.*'s study. Note that we do not expect the choice of orthographic vs. perspective projection to change eyegaze patterns of people viewing the scenes. Additional details of the scene construction may be found in [14].

3.3 Display Conditions

Stimuli were presented in the two displays shown in Fig. 1: *Orientation icon (OI)*, side-by-side 3D and 2D views, and *ExoVis*, a 3D view with three 2D projections surrounding it. Several OI designs have been proposed, with different arrangements of the 2D views. We used the design arranging the 2D views in a box shape, which maximizes correspondence between the 3D and 2D views.

We also included a strict 3D condition with a shadow beneath the ball. These were the best three out of 5 displays from our previous work, the others being strict 2D and strict 3D without a shadow. However, the eyegaze data for the strict 3D display is not discussed in this paper, as it is not a 2D/3D combination display.

3.4 Participants

A total of 9 university students (6 male, 3 female) took part in the study. The participants were naive to the goals of the experiment and had not taken part in any of our previous studies.

3.5 Eyegaze Equipment

A Tobii ET 1750 [12] infrared video-based binocular eye-tracking system recorded the gaze position on the screen displaying the stimuli, at about 30 samples per second. The manufacturer's specifications state that, after calibration using their software, the point of regard on the monitor can be determined to an accuracy of 1° visual angle across the screen. The tracker is robust to some head movement, increasing ecological validity of the method. In our experiment, the combination of good motion compensation and binocular eye tracking minimized lost data (less than 4% for most participants in these trials, with a maximum of 11%).

3.6 Procedure

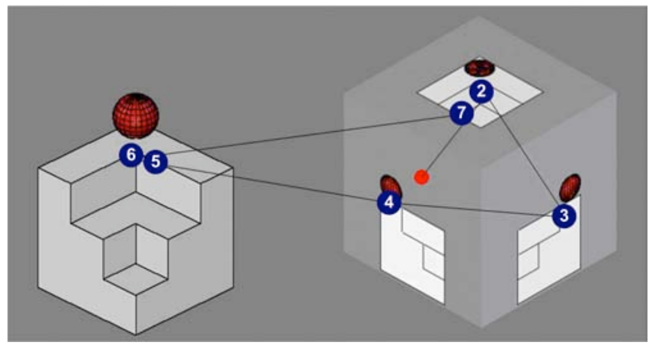
Participants stood approximately 60-70 cm from the display screen, covering about 30 degrees at the eye from one side to the other. Participants did not use a mouse. First, each participant's eyegaze was calibrated, which took about 20 seconds. After calibration, subjects reviewed instructions shown as slides on the monitor, and were given examples with answers. They then completed 5 practice trials where their answers (which were spoken aloud) were confirmed with feedback from the researcher, before starting 20 timed experimental trials (4 with each of the 5 ball heights) with one of the displays. Ball heights were in pseudorandom order and the same sequence of block/ball scenes was shown for each display and for each participant. Participants were instructed to be as accurate as possible and no time limit was imposed, trading speed for accuracy. Answers could not be changed.

Height options were displayed at the bottom of the screen, as seen in Fig 1. Subjects spoke aloud the height, for example "zero point five". An operator sitting nearby controlled the presentation of stimuli on the screen, by clicking the mouse when the subject said "Ready". The timing and display were manually stopped by the operator when the subject gave his/her answer. Another operator manually recorded the corresponding height. Eyetracking was performed throughout the experiment.

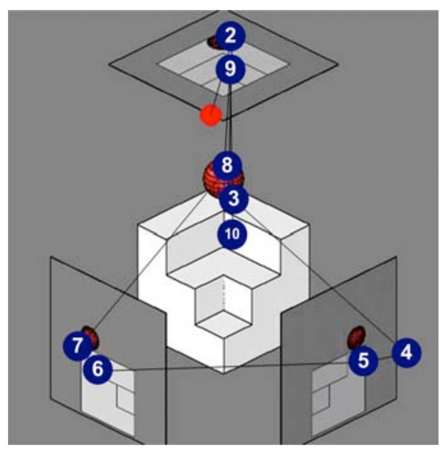
Two weeks later, the same participants were given the same task, but using a different display, and between 1 and 3 days later still, the task was performed with the third display. Display order was counterbalanced using a Latin Squares design.

3.7 Eye-gaze Fixations

Eyegaze fixations with duration of at least 100 ms were calculated from clusters of points of regard within a 1.5° visual angle, corresponding to a diameter of about 55 pixels at 70 cm distance. The fixations were overlaid on the stimuli images, and numbered in temporal order, as illustrated in Fig. 2.



(a) Orientation Icon



(b) ExoVis

Fig. 2. Eyegaze fixations in example trials for (a) Orientation Icon and (b) ExoVis. Numbered circles represent fixations in temporal order, and the lines between the dots represent the saccades between the fixations, starting at the red (unlabeled) dot. The ball is height 0.0 vertically above the top of the block.

3.8 Statistical Analysis

We analyzed quantitative results by within-subjects' analysis of variance (ANOVA) followed by Bonferroni-corrected pairwise comparisons.

4 RESULTS AND DISCUSSION

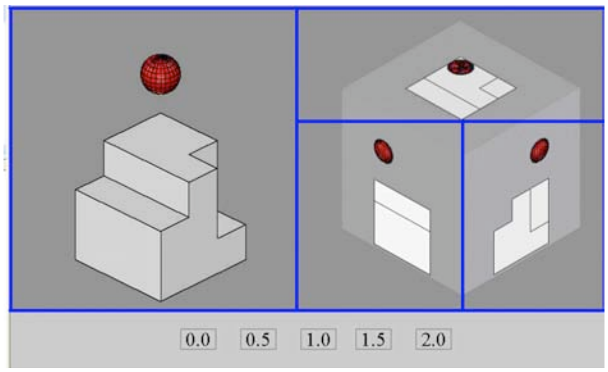
We focus on differences between Orientation Icon and ExoVis in terms of error types, viewing strategy, and fixations on each 2D or 3D view.

4.1 Performance

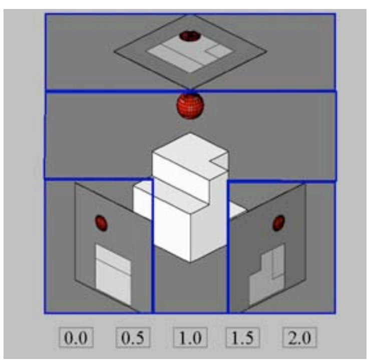
Timing and accuracy with the orientation icon and ExoVis were not significantly different overall. For the most difficult trials (height 1.5), ExoVis had fewer errors, but the difference was not significant.

4.2 Fixations on 2D and 3D Views

For the eyetracking analysis, we divided the displays into areas of interest (AOIs), as shown in Fig 3.



(a) Orientation Icon



(b) ExoVis

Fig. 3 Areas of interest for eyegaze analysis for (a) Orientation Icon (b) ExoVis. Both displays have areas called 3D, TOP, LEFT and RIGHT for the corresponding views. In this figure, the ball is height 1.0 vertically above the top of the block.

The AOIs are labeled "TOP" (for the top 2D projection), "3D" for the 3D view, and "LEFT" and "RIGHT" for the left and right 2D projections. Eyegaze on other areas, such as the height options at the bottom, were excluded from the analysis. Fig. 4 shows the percentage of fixations on these views, averaged over all subjects.

ANOVA showed a significant main effect for view type ($F(3, 24) = 10.9$, $p < 0.001$). Specifically, the 3D view was used significantly more often than TOP (p=0.002) and RIGHT (p=0.031) views, indicating the importance of the 3D view. This corresponded with participants' comments that the 3D view was important for understanding the block shape and correlating 2D views. The LEFT view was used more on average than the RIGHT view, especially for the orientation icon; however, this difference was not significant.

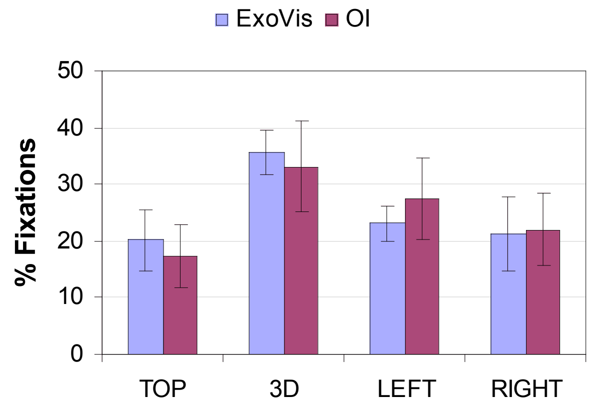


Fig. 4 Percent fixations on areas of interest for each display type, averaged over all 9 subjects. Error bars show 1 standard deviation.

4.3 Dynamics of Saccades and Fixations

To analyze viewing strategies, shifts of fixation between each AOI were compiled into transition matrices. Matrices were computed for each subject and display. Matrices for four subjects with the ExoVis and OI displays are represented as transition diagrams in Fig. 5. In these diagrams, the AOIs are shown as nodes, and the lines represent the transitions between AOIs. Thick lines represent the most frequently occurring transitions (>10% of the total for that subject and that display method), medium lines represent transitions occurring less frequently (> 5% and ≤ 10%) and thin lines represent the least frequent transitions (≤ 5%).

We also generated transition diagrams where the LEFT and RIGHT views are coalesced into a single state called SIDE, shown in Fig. 6. Information presented by the left and right views is similar, so differences between left and right are likely artifacts of their placement relative to the 3D view in the orientation icon display, rather than differences in their information content. Mean transition percentages across all participants for OI and ExoVis displays are shown on the lines in Fig. 6, and the arrows on OI values highlight percentage values that changed more than 4% from the corresponding ExoVis transition percentages. We use these transition diagrams to examine the effect of display type on viewing strategy, and the role of the TOP view.

4.3.1 Effect of Display Type on Viewing Strategy

The results show that different placement of the 3D view altered all participants' viewing patterns. The most dramatic effect is seen in the reduction in transitions between the 3D view and the RIGHT view, as shown for all participants in Fig. 5. We expect that this difference occurred because the 3D view was much farther from the RIGHT view in the OI display than in the ExoVis display. In other words, participants avoided long saccades. To compensate for fewer RIGHT / 3D transitions, there was an increase in RIGHT / LEFT and RIGHT / TOP transitions for most participants.

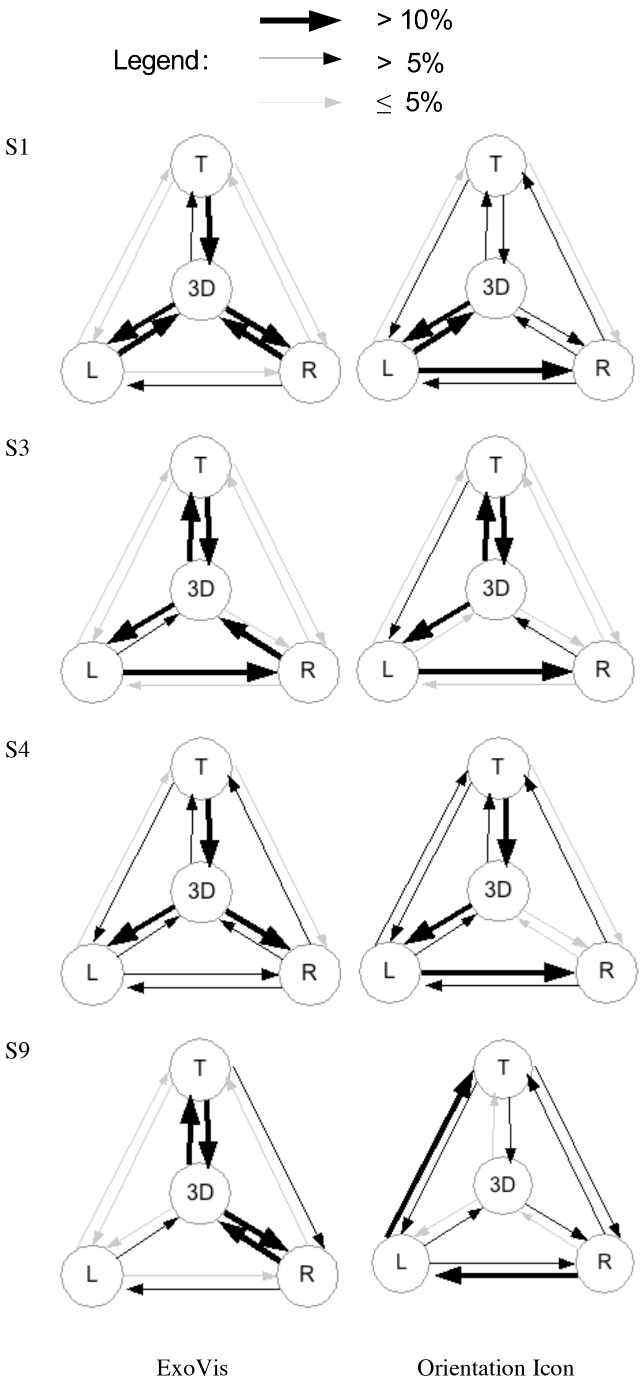


Fig. 5 Transitions for participants S1, S3, S4, and S9 using ExoVis and Orientation Icon Displays. Thick lines represent the most frequently occurring transitions (>10% of the total for that subject and that display method), medium lines represent transitions occurring less frequently (between 5% and 10%) and thin lines represent the least frequent transitions (≤ 5%) between the AOIs, shown as circular nodes. T=TOP, L=LEFT, R=RIGHT.

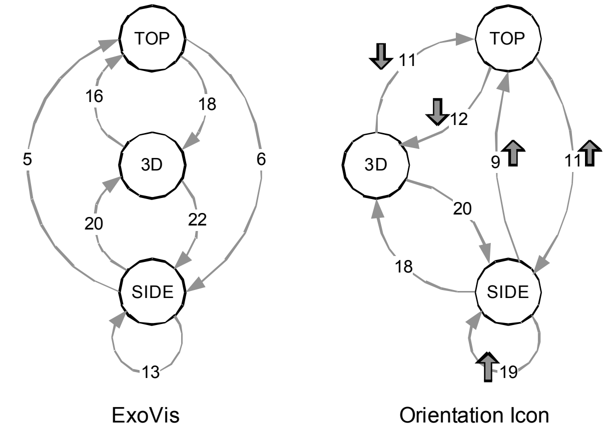


Fig 6. Mean transition percentages across all participants for ExoVis and Orientation Icon displays. The LEFT and RIGHT views have been coalesced into a single state: SIDE. Arrows on OI values highlight values that changed 4-6% from corresponding ExoVis rates.

Fig. 6 shows that with ExoVis, 76% of transitions went through the central 3D view. Participants appear to have used it as a standard of comparison for all other views. By contrast, with OI, only 61% of transitions went through the 3D view, which was not centrally placed.

We expected the TOP view to have a special role compared to SIDE views because TOP shows the pure horizontal position of the ball, not confounded by the ball height. Although the ball's horizontal position could in principle be computed using only the LEFT and RIGHT views, participants reported that the TOP view was specifically useful for this purpose. On the other hand, it is nearly impossible to compute the ball's height using only the TOP and 3D views. Some combination of 3D, LEFT, and RIGHT is necessary for height. Our eyegaze data indicates that the TOP view was viewed almost as frequently as the left and right views (see Fig. 4). Furthermore, the TOP view was used by all participants (such as in the example transition diagrams in Fig. 5). We believe that the frequency of fixating on TOP is a direct indicator of the frequency that participants checked their understanding of the ball's horizontal position

Our aggregate transition data, shown in Fig. 6, illustrate how the special role of the TOP view was maintained even as the increased distance between 3D LEFT, and RIGHT views changed their interrelationships. Total transitions into TOP were about 20% in each display. When the 3D view was in the center of the display (ExoVis), the 3D view served as the focal point, with three times as many transitions from 3D to TOP as from SIDE views. When the 3D display was moved to one side (OI), making the transition to TOP longer, the SIDE views became more of a focal point, with almost as many transitions into TOP from SIDE views as from 3D. Placing the 3D view further away prompted participants to form a new cluster, TOP / LEFT / RIGHT, which accounted for a total of 39% of all transitions in the orientation icon display. For example, participant S9 showed a particularly strong effect, having many more TOP/LEFT and TOP/RIGHT transitions and many fewer TOP/3D transitions with OI compared to ExoVis (see Fig. 5). A similar, but less dramatic, change can be seen for participant S1 in Fig. 5.

Overall, although the use of 3D, LEFT, and RIGHT varied with the display layout, the use of TOP was constant. TOP appears to have provided unique insights into the displayed data. Note that this special role of TOP reflects our height estimation task. If we had instead placed a ball on the left or right side of the object and asked the user to estimate horizontal distance, either the LEFT or RIGHT view would have displayed pure position and the other two views would have displayed distance.

4.3.2 Individual Variation in Viewing Strategies

Although most participants transitioned to the top view from the 3D view when using the ExoVis display, participant S4 was an exception. S4 used the 3D view less often than most other participants and made transitions into the TOP view almost equally from the LEFT, RIGHT and 3D views (see Fig. 5). This participant also had 2 errors with the ExoVis display (the second-highest error rate), and at least one of those errors could not be attributed to a simple height misjudgment. This indicates that using the 3D view during transitions to and from the TOP view may help users build a more accurate mental model of the scene.

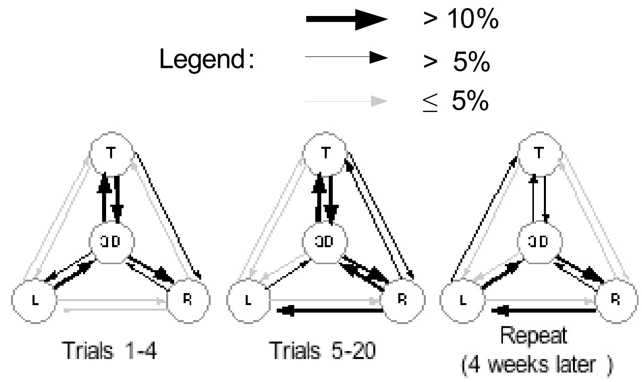
The slowest and most inaccurate subject (S7) had a high percentage of data not recorded by the eyetracker (about 11% in every slide in both OI and ExoVis), so the areas of interest and transitions matrix cannot be trusted completely. It is clear however, that S7 kept alternating the fixation gaze between the 3D and the top view, usually at least 12 times. This indicates the participant had difficulty in understanding the ball's horizontal position.

As shown in Fig. 5, with ExoVis, S9 preferred to observe 3D, RIGHT, and LEFT views in a clockwise rotation, whereas S3 (and also S2, data not shown) preferred a counterclockwise rotation. The other subjects made no such pattern. All the subjects were right-handed, so handedness does not play a role in this preference. As S3 and S9 were the quickest and were both perfectly accurate, it is not clear that "clockwise" is better than "counterclockwise" or vice versa. Interestingly, S3 and S9 also had the highest level of prior experience with 3D visualization and computer aided design tools, suggesting that visualization experts may use a more ordered viewing pattern than novices.

4.3.3 Learning a Search Strategy

Several participants showed learning effects in terms of trial time and changes to viewing strategy. S9 is a particularly clear example. S9's trial times showed a strong learning effect, taking around 9.6 s / trial in the first 4 trials, versus 5.1 s / trial for the following 16 trials. The improved time corresponds to S9's development of a gaze strategy (see Fig. 7).

Fig. 7(a) shows that S9 spent a lot of time in the early trials making transitions between the TOP and 3D views, likely building a 3D mental model and determining the horizontal ball position, before moving to the RIGHT and LEFT views for gauging the actual height. In the next 16 trials S9 began to develop the strategy of clockwise viewing (see Fig. 7(b)), looking first at the 3D and top views, then moving in a clockwise pattern through the 3D, left, and right views. Fig. 7(c) shows a repeat session with S9 4 weeks after the initial session, for which his technique was perfected – he spent minimal time on the 3D view and top projection (often viewing the top projection only once per trial) and more time on the right and left views to see the actual height. A reduction in 3D / TOP transitions was also observed with several other participants. S9's clockwise pattern from 3D to RIGHT to LEFT and back to 3D is also clearly visible in the repeat session.



(a) (b) (c)

Fig. 7. ExoVis transitions for S9 learning a search strategy. (a) average transitions for first 4 trials (b) average for next 16 trials (c) average for all 20 trials repeated 4 weeks later.

4.4 Analysis of Error Trials

Two types of errors were possible for this task: misunderstanding of the ball's horizontal position and misjudgment of the ball's height. We considered horizontal position errors to be more serious because they implied a true misunderstanding of the relative position of objects, and because height judgment accuracy could be potentially improved with measurement tools. We were curious whether OI and ExoVis differed in terms of the frequency of each error type.

We assessed error types in two ways:

- *Error size*: we expected that small errors (incorrect by 0.5 ball diameters) would be most often caused by height misjudgment, and larger errors would be caused by misunderstanding the ball's horizontal position.
- *Eyegaze pattern*: we visually examined eyegaze patterns for all error trials to determine whether the participant was looking in the correct places (indicating height misjudgment) or not (indicating position misunderstanding).

Correlation of these two measures provides reasonable confidence in the results.

4.4.1 Error Size

There were 21 error trials in total. With OI, there were 6 small estimation errors (height incorrect by 0.5 ball diameters) and 6 large estimation errors (> 0.5 ball diameters). ExoVis had the same number of small errors (6), but only 3 large errors, indicating that the centrally placed overview may be beneficial for this task. Note however, that the total number of errors was quite small, and these differences are not statistically significant.

4.4.2 Eyegaze Patterns for Error Trials

We visually examined eyegaze patterns for all error trials. The first three authors independently inspected eyegaze patterns, classifying each error as a "height misjudgment", "position misunderstanding" or "undecided". An error was categorized as a height or position error only when all decisions were in agreement. Most errors (10) were classified as a height misjudgment, but 5 were classified as position errors in OI, against 2 in ExoVis, agreeing with the error size analysis.

Furthermore, small errors were usually categorized as height misjudgment and large errors as position misunderstanding.

The reduced number of serious errors using ExoVis over the OI display suggests a potential benefit of the ExoVis display. It may be interesting to study this trend further with additional participants and more difficult trials, for which we would expect more errors.

5 Discussion

Display organization affected viewing strategy. In particular, transitions between views that were close together and central on the screen occurred more often than transitions between views that were far apart. In other words, long saccades were avoided. These observations imply that it may be better to have a centrally placed overview when the overview is very important to understanding detail views or when users need to refer to the overview frequently. However, a central overview would likely be distracting when users need to focus on detail views. Both of these situations could occur during visualization tasks. For example, when moving and orienting slicing planes within a 3D space (e.g., in a medical image viewer), a central 3D view may be valuable since users need to frequently refer back and forth between the 2D slice and a 3D overview showing the position of the slice [15]. By contrast, annotation (e.g., labeling structures) may be easiest with 2D views [17], so placing a 3D overview off to the side may be less distracting than having it in the middle of the screen.

We therefore suggest that designers study workflow for the particular tasks of interest, and arrange views on the screen to support that workflow. Specifically we suggest that frequently used views should be central, views used closely together should be placed close together, and views not frequently used together should be placed far apart.

Interestingly, the changes in viewing strategy between OI and ExoVis did not significantly alter performance. Note that our task was fairly simple; performance differences might have been observed with a more complicated task. Nonetheless, the lack of performance difference here implies that users are adaptable and can manage well with different display designs. This is reassuring, given that one display design will never be ideal for all tasks a user could perform.

6 Conclusions and Future Work

Our eyegaze analysis of a relative position estimation task illustrates several points about display design for 3D spatial data. A 3D overview image appears to be important, as it was the most frequently used view for our task. Spatial layout of views in 2D/3D combination displays strongly affected users' viewing strategy. Transitions through central views were more frequent than saccades between views that were far apart. Although the change in viewing strategy did not result in significant performance differences, our error analysis indicates that a central overview such as in the ExoVis display may reduce the number of serious errors. We might expect to see significant performance differences for more complex tasks.

In future work, eyetracking studies could be used to answer a number of questions about 2D/3D display design using more complicated and realistic tasks. For example, one could examine whether viewing strategy affects task performance, or how view strategy changes when views occlude each other in the ExoVis display. Modeling eyegaze behaviour with a cognitive or probabilistic model of the user may enhance our ability to classify and analyze eyegaze strategies. In addition, novice users could be compared to expert users to determine whether experts use different viewing patterns, as found by Law *et al.* for laparoscopic surgery training [4]. Similarly, viewing patterns of people with varying spatial abilities could be compared. Last, we suggest that a more sophisticated protocol might be able to manipulate user gaze strategy rather than merely analyze it after the fact as we did here. These stronger protocols would require monitoring gaze transitions in real time and adjusting the display to either disrupt or support a specific gaze strategy.

Acknowledgements

We wish to thank members of the Visual Information Processing Laboratory at Imperial College London, UK for performing the user studies. This work was supported by the Natural Science and Engineering Research Council of Canada (NSERC).

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