A Comparison of Interactive Shadows and Multi-View Layouts for Mouse-based 3D Modelling

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ABSTRACT

3D user interfaces allow users to view and interact with objects in a 3D scene and form a key component in many modelling applications used in engineering, medicine and design. Most mouse-based interfaces follow the same multi-view layout (three orthogonal, one perspective). This interface is difficult to understand, as it requires users to integrate all four views and build a 3D mental model. An alternative, Interactive Shadows, has been previously proposed that could improve on the multi-view's shortcomings but has never been formally tested.

This paper presents the first quantitative user evaluation (n = 36) of both the multi-view and interactive shadows interfaces to compare their relative effectiveness and usability. Participants completed three types of tasks designed to be representative of object manipulation in current 3D modelling software.

Interactive shadows were significantly better (p < 0,05) for tasks requiring participants to estimate distance. This suggests interactive shadows interface might better help users approximate relative object positioning.

CCS Concepts

• **Computing methodologies → Computer graphics → Graphics systems and interfaces**.

Keywords

3D User Interfaces; Interactive Shadows; 3D Widgets; Direct Manipulation; Human Computer Interaction; Quantitative User Studies

1. INTRODUCTION

Three-dimensional (3D) user interfaces (UIs) are software controls that facilitate the manipulation and viewing of 3D shapes and scenes. These interfaces are central to many 3D modelling applications – a form of computer-aided design (CAD) software for creating and displaying 3D scenes. The use of modern 3D CAD software has led to significant advances in a variety of fields, including medicine [4], engineering, architecture, games and film [5, 20]. Due to their wide applicability, 3DUIs have

been the focus of extensive usability research [6, 20]. However, they remain notably difficult to control as people, in general, have significant difficulty understanding virtual, abstract 3D spaces [15, 23, 36]. This often leads to a high barrier to entry for newcomers.

Modern CAD software is predominantly used on desktop or laptop machines. As such, users are typically limited to 2D input (i.e., mouse and keyboard) and output (i.e., display screen) devices [14, 33, 27]. This poses a significant usability challenge, as 2D input must be mapped to 3D object manipulation intuitively. The concept of direct manipulation can simplify this to an extent by allowing users to interact "directly" with objects in a 3D spatial context [31]. This acts as a metaphor for real-world interactions by drawing parallels between interactions with objects in the system using a mouse, and physical manipulation of objects in real life [6]. Direct manipulation 3DUIs are particularly effective for mouse-based 3D CAD systems, as they allow users to select and manipulate objects faster and with more accuracy [14, 5].

Since their inception, mouse-based 3D modelling systems have expanded significantly in terms of overall functionality, features and graphic processing [27, 5, 20]. However, the overall 3DUI layout has remained largely unchanged. Most current 3D modelling systems display the 3D scene through a multi-view interface with one perspective and three axial orthogonal views. The user can then interact with the 3D objects in the scene directly through each view, or by selecting an option from a toolbar of features. This multi-view interface displays complex information about the scene in each separate view that users must collate to form a mental model of the scene as a whole. This difficulty only increases as a scene becomes more complex.

Herndon et al. [14, 38] have proposed an alternative that addresses shortfalls in the conventional multi-view approach. Their interface starts with the orthogonal view from the multi-view interface, but encloses all objects in a cube. Each wall of the cube displays a 2D orthogonal projection (or shadow) of the objects in the 3D scene (see Figure 1). Just like with the multi-view, objects in the scene can be manipulated on all 3 axes, however shadows can only be manipulated on their 2D plane. When users interact with a shadow, the object it represents is transformed accordingly. Herndon et al. suggest that their interface design could significantly reduce the difficulty users have in generating a mental model of the 3D scene from multiple single views, as the relationship between each orthogonal view and the full 3D scene is visibly integrated. The interactive shadows interface has to our knowledge not been empirically evaluated, nor quantitatively compared to the current standard multi-view interface.
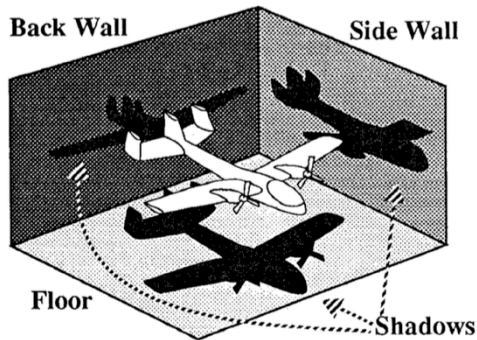
Figure 1: A model airplane displayed in the interactive shadows interface. Note the opaque shadows of the model are projected onto the floor and both walls. To prevent occlusion only walls behind the object are displayed. [14]

In this paper, we build on Herndon et al.'s work by critically evaluating and comparing their interactive shadows interface with the conventional multi-view interface [14, 38]. We aim to determine whether one interface is significantly more effective or usable than the other. Herndon et al. state that their interface is likely to be most appropriate for certain types of tasks. As such, we developed three separate tasks that together represent a range of typical object positioning tasks in 3D modelling software.

Participants performed significantly better in terms of object positioning (distance) accuracy (r = 0, 237; p < 0,05) in our type 1 task. We found little other evidence to support a claim that one interface is more usable and useful than the other. This paper contributes by building on prior 3DUI research, and identifies key features for future researcher.

2. METRICS FOR 3DUI EVALUATION

Research into the usability of 3D technologies has, for many years, focused on creating new and innovative interaction devices and techniques. Novel methods to interact with 3D space have been devised, but have, to a large extent, not been evaluated in terms of usability [6, 9]. This has left the field with a lack of evidence as to the quality of many existing 3DUIs. Furthermore, there are few concrete guidelines for how to quantitatively assess the usability and usefulness of 3DUIs [5, 6, 29]. To encourage research into this area, experts suggest using metrics initially developed for 2D and more generic graphical UIs [6].

2.1 Task Performance Metrics

These metrics involve data gathered on how effectively the user can accomplish required tasks in the user evaluation. These metrics are specific to the goal of the software system being evaluated [20]. There are three categories of tasks that all 3DUIs must facilitate:

- *Scene navigation tasks* – 3D environments are usually quite complex and cannot be understood and manipulated accurately from a single perspective [37, 20]. Scene navigation tasks relate to user altering their viewpoint within the 3D world, such as by zooming or panning.

- *System/Application control tasks* – these tasks affect how 'in control' the user feels over the system's behaviour. They involve how users communicate their intentions with the

system, such as using the mouse-cursor to point-and-click on an element in the UI.

- *Selection and manipulation tasks* – these refer to how the user interacts with 3D objects within the scene and predominantly involve object positioning, rotation and scaling tasks [20]. In this context, the user must be allowed to complete these tasks as precisely and efficiently as possible [17, 29]. These are primary functions of modelling software, and are the major focus of 3DUI research.

Research into 3D CAD software has resulted in several well-tested techniques for scene navigation and system control; there are now accepted conventions for these tasks best suited to specific scenarios [5, 20]. In the evaluations of CAD 3DUIs we therefore instead focus on object selection and manipulation and the speed and accuracy with which the users can complete them [17]. It is important to note that this metric does not account for how much the user enjoys using a system, but rather how well they performed. These metrics cannot be interpreted in isolation, as user preferences may significantly affect task performance [6].

2.2 User Preference Metrics

User preference metrics focus on the individual user's experience of the 3DUI, such as how easy the system is to use, how long it takes to learn, and how satisfying it is to use [6]. There are reliable, validated questionnaires such as the System Usability Scale [7] that have been developed to measure these outcomes, as well as more qualitative interviewing approaches [6, 29].

User preference metrics also provide quantitative insight into user comfort – the user's subjective experience of physical, emotional and mental well being while using the application [14, 20]. Users are also more likely to evaluate the usability software negatively as their experience has been uncomfortable.

3. RELATED WORK

To our knowledge, there have been five publications (summarised in Table 1) that empirically evaluate mouse-based 3D scene manipulations in various scenarios. All required participants to select, position, resize, and/or rotate objects using the mouse. They then evaluated participant task performance on speed and/or accuracy. Most evaluated user preference metrics as well, with the exception of Hubona et al. [17], who focused purely on a qualitative analysis.

Unfortunately, these evaluations exhibit methodological limitations around their choice of participants. Firstly, the sample size for the majority of these experiments is quite low, with Oh and Stuerzlinger [27] and Jáuregui et al. [21] having only 10 and 12 participants, respectively. Such a small sample size is useful for a pilot study, but usually cannot be used to infer anything about the general population. The second issue is a lack of generalizability. Variability in visuospatial reasoning, learning ability, gender, and prior experience leads to a wide range of performance with 3DUIs for non-expert users. People from different backgrounds vary greatly when it comes to inherent skill, learning ability, and previous familiarity with these systems. Gender could play a role in a person's ability to interact with 3D virtual environments, as males generally have higher visuospatial abilities than females [18, 34]. Thus a participant sampling method that does not account for these factors can affect the generalizability of the study's findings.

Table 1: Summary of experimental methods used by quantitative evaluations of mouse-based direct manipulation 3DUIs

Experiment	Tasks	Subjects	Task Performance Metrics	User Preference Metrics
Hubona, Shirah, and Jennings [17]	Relative object positioning and resizing	Females: 14 Males: 16	Speed, accuracy	None
Oh and Stuerzlinger [27]	Relative object positioning	Females: 4 Males: 6	Speed	Preference
Rizzo et al. experiment 1 [29]	Object selection and release, relative translation and rotation	Females: 10 Males: 10	Speed, accuracy	Ease of learning, cumbersomeness, fatigue, comfort, preference
Rizzo et al. experiment 2 [29]		Females: 12 Males: 12		
Smith, Salzmann, and Stuerzlinger [33]	Relative object positioning	Females: 2 Males: 13	Speed, accuracy	Preference
Jáuregui, Argelaguet, and Lecuyer [21]	Object selection and ordering	Females: 2 Males: 10	Speed, accuracy	Preference, comfort

Only Rizzo et al. [29] intentionally balanced the genders in each experiment they conducted. They were also the only study that acknowledged and accounted for the effects of varying educational and cultural backgrounds. In their study, Rizzo et al. measured visuospatial ability using the Mental Rotations Test (MRT) [28] and found that males performed significantly better than females. However, there were no significant differences between the genders in performing the 3D selection and manipulation tasks using a (2D) mouse. This suggests that visuospatial ability may not directly predict 3D manipulation performance with a mouse. It also indicates the gender imbalances in the other studies may not have affected their results. However, it would have been useful to have data supporting this claim. Culture and/or educational background were also identified as possible contributing factors to visuospatial ability. Interestingly, Rizzo et al. also found that prior 3DUI experience had no statistically significant effect on user performance in 3D interaction tasks.

The ease of learning a 3DUI can have a noteworthy influence on the user's qualitative and quantitative results in such a study. If the interface is too confusing, the user can quickly lose interest and become frustrated [14]. This ties in with the fundamental 3DUI concepts of direct manipulation and system control, where the user should always feel in complete control of their actions [20, 26, 31]. One way to effectively ensure the user is comfortable with the interface is to have a short introduction or tutorial exercise before the study begins. A number of 3DUI evaluations have found this approach helpful [33, 27, 36].

The final potentially confounding factor present in a number of 3DUI experiments is participant fatigue. To critically evaluate each interaction task for an interface can take a long time (according to Bowman et al. [20] more than 30 minutes can be considered lengthy). Participants' task performance and user preference metrics both suffer if users are required to take part in such prolonged experiments [6]. It is advised that experiments are kept shorter than 30 minutes, however such short experiments can reduce the significance of results, as the study cannot analyse as many factors. For multiple separate tests within an experiment, the participants could be given a break in-between to reduce their fatigue. The studies that evaluate the differences between two or more systems usually use the latter tactic [6, 29].

These studies are all helpful in understanding the problems faced by 3DUI researchers. Unfortunately, due to their vastly different participant groups and overall research focus, their results are difficult to compare. However, there are two main findings applicable to improving the interfaces used by modelling software:

- Users find it difficult to perceive depth in virtual 3D environments. Using effects drawn from real-world interactions such as shadows and occlusion can be helpful in reducing inaccurate depth perception [17, 27, 21].
- Interactions confined to a 2D plane are very helpful in ensuring quick, accurate selection and ordering tasks [33].

Herndon et al.'s interactive shadows interface [14, 38] incorporates these two aspects. The shadows are used to help users perceive depth in the scene without occluding part of the actual object. The interactive nature of these shadows is confined to their 2D projection plane and thus could improve the speed and accuracy of selection and ordering tasks. Tory et al. [36] performed an evaluation using an implementation of this interface as a non-interactive visualisation tool. This study focused purely on the participants' understanding of the 3D scene, presenting them with static screenshots of the interface. Participants were able to estimate relative position and orientation with a significantly higher accuracy than when compared with the standard multi-view interface.

To our knowledge the interactive shadow interface has never been formally evaluated for its effectiveness as a direct manipulation 3DUI. As it incorporates both findings discussed above, and has been shown to be an effective visualisation tool, we believe it could be a viable alternative, and possible improvement, to the conventional multi-view interface.

4. TECHNICAL APPROACH

For the purposes of this study we require high quality implementations of the interactive shadows and multi-view interfaces. These implementations should be representative of existing 3DUIs. As such, we considered creating our interfaces as extensions to existing software packages. However, existing 3D modelling systems are highly complex and typically incorporate a diverse range of features. Many of these features are not required for this study and could confuse and distract users. For this reason

we implemented our interfaces independently, incorporating the minimal functionality required for our experimental evaluations. This section discusses the specific requirements and design decisions of our technical implementations of the interfaces.

4.1 Multi-view Interface

We implemented our interface to match the standard multi-view interfaces found in 3DS Max, Blender and Maya. Our representation can be seen in Figure 2 (left). As in conventional software, the side, top and front views (labelled) allow users to manipulate each object on YZ, XZ and XY planes, respectively. In the perspective view users can manipulate the object on any axis desired. Each view is labelled to emphasise that the interface has been divided into four separate views.

In each of the orthogonal views we display gridlines in a unique colour to give users some concept of the scale in the scene, as well as to emphasise that each view shows the scene from a different axial direction.

4.2 Interactive Shadows Interface

This interface (Figure 2 (right)) shows a single perspective view of the 3D scene with a "box" surrounding it. Each side of the box shows a projection of the scene as seen from that side. This projection acts as a shadow, where every side of the box shows the shadows that objects in the scene would cast on that side. Users can interact with the objects through their shadows, as well as with the objects directly through the main view. This interaction is shown in Figure 3. The shadows can be manipulated on only two axes; in the same way one can manipulate objects in the plane of the orthogonal views in the multi-view interface. The user can view and modify objects from any of the scene views.

This interface has similar gridlines to the multi-view interface to help users orient themselves within the scene. These gridlines are projected onto the walls of the box, as we found that including them in the centre of the scene obscured geometry.

Our implementation differs from Herndon et al. in several ways. Herndon et al. allow users to control the rendering style of shadows to configure how much detail they would like to see in different tasks. This would be desirable in a professional 3D modelling suite, but was out of the scope of this project. In addition, the shadow style selected by participants could affect their overall experience of the interface and thus confound our results. We chose to implement the 'mirror' version of the shadows that displays all attributes of the objects clearly. This shadow style is the most generally applicable, as opaque or wireframe shadows would limit users on certain tasks such as ordering objects. Our shadows are slightly darker than the true mirror shadows used by Herndon et al., as pilot test feedback

indicated that the difference between the original object and it's mirrored shadow was unclear.
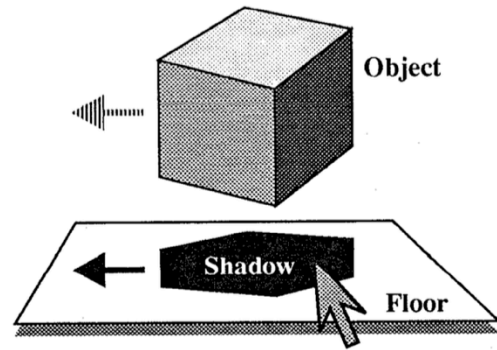

Figure 3: Translating the shadow of this cube on the floor plane applies the translation to the cube by the same amount in a plane parallel to the floor plane. [14]

4.3 Features

We surveyed popular 3D modelling software packages to determine which basic features our interfaces require to be representative of existing 3D modelling software. We outline the features we incorporated below, drawing your attention to the screenshots of our interface implementations in Figure 2.

4.3.1 Translating Objects

Clicking the "Translate" icon on the top left of either interface enables a mode allowing users to select and translate all movable objects. To select an object, the user hovers their mouse over it and presses the left mouse button. A selected object's edges are highlighted to indicate this status. To move the object, a user holds down the left mouse button and drags the mouse to where he or she wants the object positioned.

Our implementations handle translation by creating an invisible, virtual plane in the scene at the selected object's centre, with the plane normal to the camera view direction. As the user drags the mouse, the object is moved along this plane in the direction of the mouse cursor. This gives the appearance of smooth movement, directly parallel to the user's view of the scene.

4.3.2 Rotating Objects

This interaction is similar to translating. Clicking the "Rotate" icon on the top left of the interface enables the rotation mode. Selecting an object to rotate uses the same hover and left-click approach. To rotate this object, the user needs to hold down the
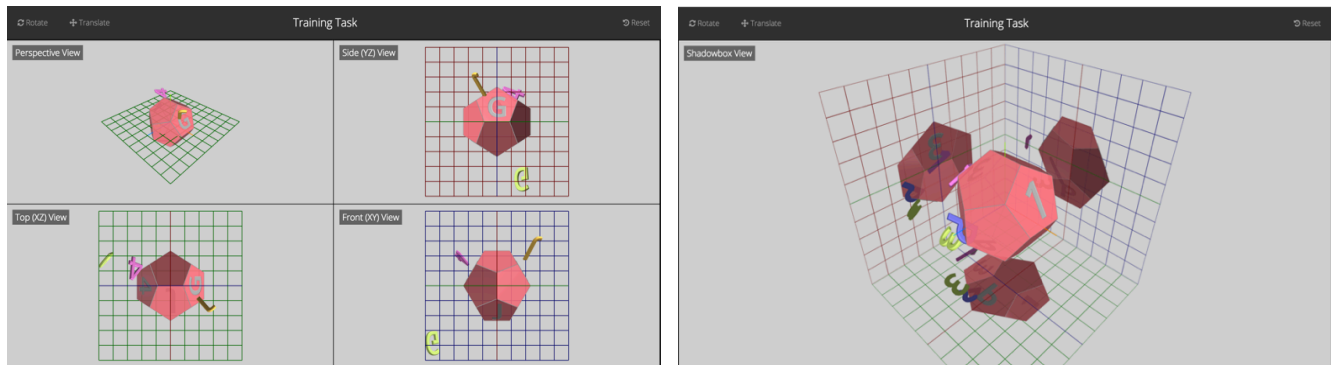

Figure 2: Our implementations of the Multi-view (left) and Interactive Shadows (right) interfaces taken during the training task before the experimental evaluations began.

left mouse button and drag the mouse in the desired rotation direction.

Rotation is handled using the Arcball controller approach [32]. The Arcball controller uses a virtual sphere centred on the object's position. The position of the user's mouse is then projected onto points on the sphere's surface. Mouse movement causes the object to roll, as if the user were pushing a ball in that direction. Mouse movements outside the sphere are interpreted as Z rotations.

4.3.3 Scene Manipulation

The users are able to zoom in or out, rotate and pan their scene using the mouse in order to view the objects from a desired position.

Users can scroll the mouse wheel up or down in order to zoom in or out of the view currently in focus.

Left-clicking and then dragging on the scene rotates it in the direction of the mouse drag. Note that scene rotation is disabled for orthogonal views in the multi-view interface.

Right-clicking and then dragging pans the scene in the direction of mouse movement. This works in all views.

4.3.4 Resetting

We incorporated two forms of reset in our designs. The user is able to reset objects to their initial position, as well as the scene orientation to its original alignment.

Pilot testers found it useful to be able to reset the objects to their original positions if they lost them within their scene. This could happen if users used multiple combinations of scene and object manipulations such that the objects in the scene are no longer visible.

4.4 Implementation

As this software is intended to facilitate our experimental evaluations, we wanted to ensure that it would be easy to install and run. We decided to use a web-browser based approach, as this makes it easy to deploy to each testing computer. Recent advances in WebGL meant that we could create our interfaces to run in the browser and handle any 3D interactions with negligible performance impairment. We chose to implement the interfaces using three.js [7], an open-source JavaScript library that allows developers to quickly write complex WebGL applications.

We hosted the implementation on Github Pages [11], a static hosting service. To store the participants' various interactions with our system, we used the LocalStorage JSON API. This stored the data on the local machine, which could be downloaded manually by the invigilator after the participant had finished. We also stored the participant's current position in the experiment pipeline in LocalStorage to ensure that if they closed the browser window, or the computer crashed, they could continue the experiment from the same position.

To ensure that the implementation of both interfaces is on a par with existing 3D CAD systems, we conducted a formal heuristic evaluation. We approached four 3DUI experts to review early iterations of our implementations with Nielsen's Revised Heuristics [25].

On later iterations of our experiments we ran a pilot study to test the evaluation procedures with 9 undergraduate students majoring in Computer Science. The pilot study was conducted under conditions matching intended experimental procedure discussed at length in section 5.3. After their participation, we conducted an informal debriefing to collect feedback. These pilots found key flaws in the clarity and flow of the application that might have negatively affected our final study results. Our initial study design incorporated more iterations of each task, which took participants 55 – 70 minutes, and testers reported feeling fatigued. To rectify this we reduced the amount of tasks per task type. Testers also reported that the distinction between objects and shadows was too small. Thus we modified the mirror shadows to be slightly more opaque.

5. EXPERIMENTAL METHOD

In this study we performed a randomised single factor repeated-measures experiment to compare and contrast our two interfaces. Our independent variable is the type of 3D interface used, as we wish to measure the effect on participant performance when this is varied. The dependent variables are the task performance and user preference metrics we measure.

For task performance metrics we measured the speed and accuracy of task completion. Speed is operationally defined as the time in seconds it takes for the participant to complete a task. Accuracy is the measure of how close the participant's submission matches the model answer for the task. We captured two measures to represent accuracy, namely unit distance and orientation difference. Distance is the difference in units between the participant's object and the target position. Difference in orientation was calculated by determining the minimum angle (in radians) required to rotate the participant's object to match the target object's rotation.

We collected qualitative feedback by asking open-ended questions about the participants experience during the study. This gives another dimension to the quantitative data by helping us to interpret the results more accurately in context [20].

In our experiments the order and type of tasks carried out by participants for each interface remained consistent throughout the experiments. Equal numbers of male and female participants were randomly assigned to each experiment group and the order in which the participants evaluated the interfaces was counterbalanced. We measured the 3D interaction ability using the Mental Rotations Test (MRT) [30] as this has been shown to positively correlate with a person's performance in 3D manipulation tasks. Other aspects, such as the participant's experience with 3DUIs, were recorded in a pre-experiment questionnaire.

5.1 Participants

Participants were recruited through a non-probability sampling method, using a combination of convenience and purposive sampling techniques. The study was advertised via physical posters on the university campus, as well as through social media. A monetary incentive of 30.00ZAR was offered for participation in the study. We were careful to choose a monetary value that would not be disproportionally motivating to participants.

Each participant who responded was screened using a modified version of the Survey of Spatial Representation and Activities (SRRA) [34] that we distributed online. The survey captured demographics, education, computer literacy and other factors that have been shown to correlate with mental rotation ability such as experience playing video games or using maps. As the experiments would require basic computer literacy skills, we ensured all participants that were accepted did not list themselves as less than "moderately skilled" with computers. We also intentionally recruited equal numbers of men and women to ensure that we represented both genders equally.

There were 36 students in the final study, all living in Cape Town, South Africa, and aged 19 - 26.

Participants were issued an informed-consent form on the day of the experiment, as well as a breakdown of what they were being remunerated for. They were given time to read these documents and ask any questions. If they agreed to participate they signed the documents and were seated for the experiments.

5.2 Task Design

We designed 3 types of tasks for participants to complete during their experimental evaluation. These tasks were chosen as they represent common interaction scenarios in 3D modelling applications. Participants were instructed to complete each task quickly and accurately and press the "submit" button once done. Each task was completed more than once to get an average performance per task for each participant. The specifications of these tasks are outlined below.

5.2.1 Task Type 1: Plane Alignment

Plane tasks require the user to line up the letter or number object in the scene with the centre of the black plane in the scene (see Figure 4). The goal is that the object lies flat in the centre of the plane, so the plane appears to make a bisection of the object. The orientation of the object about the normal to the plane, once it is in this position, does not matter. The plane is fixed; only the object in the scene can be translated and rotated. When the task loads, the object is generated at a random position within a 400x400 unit cube centred on the origin.
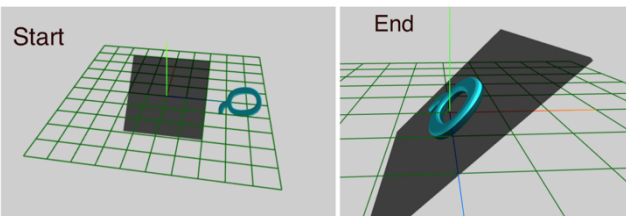

Figure 4: Example of the plane task with the initial scene layout on the left and the desired submission on the right.

These tasks were chosen to assess how the interface type affects the participant's ability to estimate the relative position and orientation of objects.

5.2.2 Task Type 2: Dodecahedron Template

A regular dodecahedron in the centre of the scene has a cut-out template on one of its faces that corresponds to a number or letter object that is also visible in the scene (see Figure 5). This task requires participants to slot the object into the cut-out in the dodecahedron. Only the letter or number object can be translated and rotated. The dodecahedron is stationary.

For these tasks we ensured that the letter or number object placed in the scene had no axes of symmetry. This prevents there being
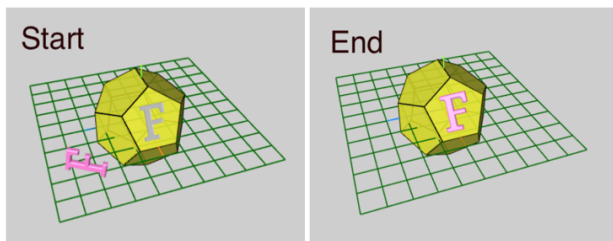

Figure 5: Example of the dodecahedron task with the initial scene on the left and the desired submission on the right.

more than one correct way to slot the object into the cut-out. We selected these tasks to identify participants' ability to accurately match an object's position and orientation given an explicit goal orientation and position. This differs from task type 1 as here participants are expected to match an example whereas in task type 1 we requested their best estimate.

5.2.3 Task Type 3: Room Construction

These tasks require the participant to align the objects in the scene to construct a mock living room (see Figure 6). The participant must place the table onto the tiled floor so that it is centred on the highlighted (orange) rectangle, and the table legs touch the floor. Then, they must place the lamp onto the table in the centre of the highlighted circle. For these tasks we measure the accuracy in terms of relative orientation and position within the scene. The table, floor and lamp must have the same orientation relative to one another.
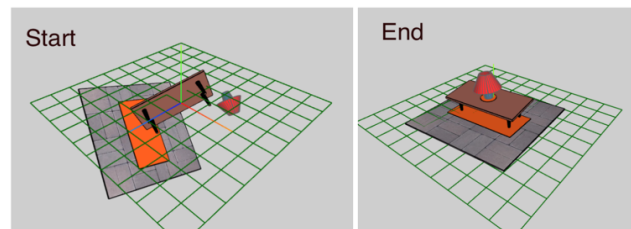

Figure 6: Example of the room task with the initial scene layout on the left and the desired submission on the

The objects in this scene have multiple axes of symmetry. To calculate accuracy in radians we translated the user's objects to the XY plane and removed all Z rotations. In this scene all three objects can be translated and rotated.

These tasks were designed to mirror real-world use-cases of 3DUIs. The two previous types of tasks test certain aspects of user interaction, but they are less representative of real 3DUI uses, since certain objects are static. The room alignment tasks require participants to set up a scene, which is something animators and architects frequently do when using their 3D CAD tools [23].

5.3 Procedure

Experiments were conducted in an access-controlled computer laboratory. Only participants and the invigilator were present at all times to ensure participants would not be distracted. Each participant was allocated a desktop with screen, keyboard, and mouse of the same make and model. Participants were allocated a participant number, which was attached to their signed informed consent form.

The experiment took place exclusively in one application pre-opened on the screen in front of the participants. The application prompted participants for input when required and included all necessary documentation. This outlined each step of the experiment one by one and explained each interface and task individually. A copy of this documentation was provided in hard-copy form as well at the beginning of the experiment to allow for easy reading and annotations if required.

Participants were given 10 minutes to first complete the MRT [30] to assess their mental rotation ability. The system did not give participants the option of proceeding to the next section of the experiment if they completed the test in less than 10 minutes. This was done, as the original paper-based version of the test requires participants to take the full 10 minutes [30]. We wanted to ensure our test parameters were consistent with the original. The system emphasised that participants should try to complete the MRT as

quickly and accurately as they could without guessing the answers.

After the MRT the evaluation of interfaces stage of the experiments began. This involved documentation introducing the 3 types of tasks, interface controls and the first interface they would be evaluating. Once ready to proceed, each participant was then allocated 3 minutes to familiarise themselves with the interface in a training task environment. This allowed them to explore the interface and gain familiarity with the controls. After this, they completed four type 1 tasks, three type 2 tasks, and two type 3 tasks. The number of times each type of task was repeated was determined by the complexity and possible duration of each task. Participants could move immediately to the next task upon completion of the current task.

Once they completed all tasks, participants filled out a questionnaire to evaluate the interface. This questionnaire included a number of open-ended questions regarding the degree of control that users experienced, as well as a structured System Usability Scale (SUS) [7]. The SUS allows us to quantitatively measure the usability score of each interface.

6. RESULTS & DISCUSSION

In total, we had 36 participants who completed 18 tasks each – four type 1, three type 2, and two type 1 per interface. Each participant also completed two usability questionnaires. Thus we had 1944 task results and 72 usability results.

This research aims to compare a participant's performance across the interactive shadows and multi-view interface for each task type. Additionally we must compare the overall evaluation of each interface by each participant. As such, we required multiple two-paired-group comparisons. Our first step was to determine data normality so as to identify which statistical comparison test to use.

We ran a Shapiro-Wilkes test to identify the normality of our data distribution per task per interface. This showed that our data was entirely non-parametric. We ran an additional Smirnov-Grubbs outlier test on each task measure and identified a large number of outliers. In such cases it is helpful to perform a base-10 logarithmic transform on each data point. A log transform can help normalise the distribution of measured data to reduce the effect of outliers on the distribution. After we performed this transform our data distribution was much closer to a normal bell-curve and Smirnov-Grubbs test found fewer significant outliers.

After analysis we found that all outlier values detected either had a distance accuracy measure of worse than 50 units or an angle accuracy of worse than $\pi/3$. These values both yield a visibly incorrect submission. This could happen if the system had a glitch

for that particular trial or the participant was not concentrating on the task well. An example of this was a participant that accidentally clicked the submit button for a task twice in quick succession, effectively submitting the newly loaded task within 0,1 seconds.

We removed a total of 33 data points that the Smirnov-Grubbs test identified as outliers. We used the rest of the data in calculating each participant's average for each performance metric per task, per interface. For each type of task we analysed the distribution of the performance metrics (distance accuracy, angle accuracy and speed) for each interface. The Shapiro-Wilkes test identified that our data was close to normal across each data category, however not all had a p-value < 0.05. Thus we chose to analyse our data using a comparative two-tailed test that does not strictly rely on the assumption of a normal distribution – Wilcoxon Signed Rank test (a = 0.05). A summary of the analyses can be found per performance metric below. We display the medians rather than means, as this is a better representation of the mid-point for non-parametric distributions. Figure 7 displays the bar chart representation of our descriptive statistics for each performance measure.

6.1 Distance Accuracy

Our initial descriptive statistic analysis identified differences in medians between the two interfaces for all three types of tasks.

We then performed inferential statistical analysis to determine whether any of these differences were significant. The summary of this data is displayed in Table 2. For type 1 and type 2 tasks the Interactive Shadows interface has a lower median, while for type 3 tasks the median multi-view interface was lower.

Table 2: Results and statistical analyses of distance accuracy

Task Type	Interactive Shadows Med	Multi-view Med	Med Differ-ence	Effect r	p-value
1	4,768	6,026	1,258	0,237	**0,044**
2	16,934	17,082	0,148	0,130	0,270
3	3,012	2,876	0,136	0,072	0,540

We found a significant difference in the two interfaces for type 1 tasks. Our analysis identifies that the interactive shadows task is more accurate in terms of distance for these types of tasks (median difference = 1,258; r = 0,237; p < 0,05).

The significance of task type 1 could be attributed to the specifics of this task category. These tasks required participants to estimate the centre of the plane and the letter/number object and place the object onto this centre. The other tasks clearly mark the target
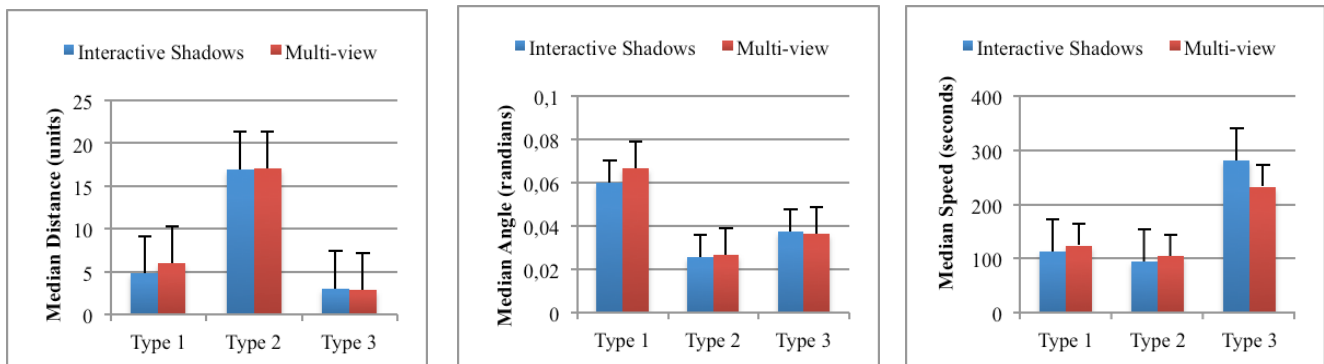

Figure 7: Bar charts with error bars (95th confidence level) showing the median performance measures per task type.

location that participants are required to match with their object. Previous studies into shadow depth cues have shown they help users effectively approximate relationships between objects in the 3D scene [17, 35, 36]. This result shows promise that the interactive shadows interface could be useful for tasks in which users must estimate object positioning.

As our tasks are not individually comparable we cannot safely run a test to gain quantitative insight into the large disparity in medians between task type 1 and type 2. This difference could be insignificant, however previous studies have shown that object manipulation can be significantly impaired if the objects within the interface obscure one another [17, 20]. In task type 2 the dodecahedron obscures the views of the scene a great deal whereas the plane in task type 1 did not. It is possible that this occlusion had an effect on participants' ability to judge distance effectively.

6.2 Angle Accuracy

Similar to distance accuracy, participants performed better for task types 1 and 2 in the interactive shadows interface while performing slightly better in the multi-view interface for type 3 tasks. This difference was only apparent in the descriptive statistics. Our Wilcoxon Signed Rank test yielded no significant results for any task type. The summary of this data can be found in Table 3.

Table 3: Results and statistical analyses of angle accuracy

Task Type	Interactive Shadows Med	Multi-view Med	Med Difference	Effect r	p-value
1	0,060	0,067	0,007	0,122	0,300
2	0,026	0,027	0,001	0,058	0,626
3	0,037	0,037	0,001	0,168	0,153

Due to the lack of significance in all types of tasks, it is possible that the level of accuracy required to align the orientation of objects in the 3D scene is enabled by both interfaces. This would be consistent with previous research that identifies the orthogonal views as those crucial for high accuracy interactions like these.

All task types have similar angle accuracy. This could indicate that despite being different tasks they all test the same type of object orientation. It is possible that more complex orientation tasks could have yielded different results.

6.3 Speed

Our speed descriptive statistics also identify the interactive shadow as more accurate than the multi-view for type 1 and 2 tasks but less accurate for type 3. After performing our Wilcoxon Signed-Rank test we determined that this observed difference was not significant. These results are summarised in Table 4.

Table 4: Results and statistical analyses of speed

Task Type	Interactive Shadows Med.	Multi-view Med	Median Difference	Effect r	p-value
1	91,552	108,393	-16,841	0,191	0,105
2	76,958	85,402	-8,444	0,080	0,496
3	227,200	217,697	9,503	0,142	0,229

This performance metric may have been significantly affected by participants' individual behaviour during the study. A number of participants spent a long time trying to perfect their submissions. They were explicitly instructed to perform as quickly and accurately as possible, but this instruction is vague. It is open to interpretation and bias depending on the preferences of the individual participant. As such, some participants prioritised speed while others prioritised accuracy.

The difference in time taken between the first two task types and type 3 is due to the complexity of this last task category. Task type 3 required participants to manipulate and arrange three objects in the scene and all three could be interacted with. As such the task was much more complex than the first two which had only one movable object.

6.4 Usability Score and Feedback

Our quantitative SUS questionnaires return a percentage measure representing user comfort, ease of use and learning, and confidence in using the system. The resulting data for each interface was non-parametric and we thus used medians to compare our descriptive statistics. Interestingly evaluation medians were identical (m = 47,5). To determine whether there was any interaction we could not see through our descriptive statistics we ran a Wilcoxon Signed-Rank test. The result determined that users found no significant difference between either interface types.

In terms of qualitative user feedback, however, users did identify differences between the interfaces. We found that users were quite positive about the interactive shadows interface. Of our 36 participants 20 identified that they preferred the interactive shadows interface for all types of interactions. A further 8 identified it as better than the multi-view interface for making specific, fine-tuned accuracy manipulations.

We had 4 participants that were used to interacting with 3D modelling or manipulation software. These participants did not enjoy the interactive shadows interface and also expressed difficulty transitioning between the interfaces after evaluating the first one. Novice 3DUI users did not express difficulty in this respect. Three participants reported no interface preference.

A few participants mentioned that they preferred the multi-view interface in theory, but they felt limited by screen size, as the same screen dimensions were shared by four individual views, whereas the interactive shadows interface only displays one view.

Our qualitative feedback identified certain weaknesses in our experimental design. We found users focused on UI and hardware design issues that were often based on preferences. User responses repeatedly identified usability aspects that were present in both interfaces. Only when explicitly asked to compare the interfaces in the final qualitative question did users give comparative feedback.

While invigilating experiments, we noted that some of our participants became frustrated with the interfaces base on their demeanour and verbal outbursts. A number of our participants that had not experienced a 3DUI before found the direct manipulation mapping difficult to grasp at first. Observing their behaviour we saw that they often used their hands to visualise the 3D rotation or translation before using the mouse to execute this action. This frustration was only prevalent during the first interface they evaluated.

6.5 Covariate Factors

In an attempt to control for confounding variables in our experiments we collected data on twenty-six categories that could affect participant performance. These categories involved demographics, educational background, and exposure to hardware and software and in particular, exposure and use of 3D software. We also collected users' MRT scores due to its significance in previous studies discussed in Section 3.

We performed multiple within-subjects analyses on our interfaces with these categories of data using the two-tailed Wilcoxon Ranked-Sign (a = 0.05). We found that the MRT had a significant effect on the distance performance of participants in each interface individually, but had no effect on the difference in performance between interfaces. We also determined that gender had no significant effect on participants' performance across all tasks. Participants having had prior experience with 3D modelling or gaming software significantly impacted their speed and angle accuracy, but had no significant effect on their distance accuracy.

7. CONCLUSION & FUTURE WORK

We performed a quantitative evaluation of the interactive shadows and multi-view interfaces to determine whether one was more useful or usable as a 3DUI for three classes of tasks.

We were able to identify that the interactive shadow interface is significantly better for accuracy in terms of distance when completing our type 1 tasks. The difference between this task and the other two types is its lack of demarcated target position. As such this shows promising evidence that the interactive shadows interface could be more effective than the multi-view interface for tasks that require users to make estimates about relative position between objects. This avenue could be explored further by pursuing a similar study with comparable tasks with varying levels of positioning requirements.

Unfortunately, we were not able to identify whether our two interfaces affected participant performance significantly on any other performance measures. This could be due to the design of our task classes, or the way our participants interpreted their "quickly and accurately" instruction. In future it would be valuable to study various complexities of comparable tasks so that we can explore the interface's effect on performance on a task more thoroughly. We also suggest separating the "quickly and accurately" instruction and focus one them individually. This would reduce the risk of a double-barrelled instruction eliciting unpredictable responses from participants.

This research set out to contribute to the lack of empirical evaluations of 3DUIs used in modelling software. Our formal evaluation takes the first step to determine empirical relative effectiveness between the current standard interface and a potential alternative. While our results lack significance, they show potential for further investigation in this area and the opportunity to improve 3DUI manipulation for specific tasks.

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