A Survey of Mouse-based 3D Scene Manipulations Focusing on 3D Modeling Software

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Modern 3D modeling software packages use the same basic user interface for building and manipulating 3D scenes. There no is literature noting the reason for this convention, nor evidence to support that this interface is empirically better than any alternatives. This literature review thoroughly examines the 3D user interface theory, and which aspects in particular are relevant for the design and progress of mouse-based 3D modeling systems. In this process I highlight that there is a distinct lack of research into object selection and manipulation tasks, which are central to 3D object manipulations in modeling systems. I then identify the core methodologies to evaluate 3D user interactions, and the importance of analyzing user speed and accuracy performance metrics alongside user preference metrics, such as presence, learnability and comfort. I go on to analyze five relevant experimental studies and highlight common flaws and confounding factors that must be accounted for in more rigorous ways in future research. All succeeded in achieving statistically significant results, but had very small and unstandardized participant groups. I determined that two topics that do show promise for modeling systems are depth cues and 2D manipulation constraints. Researchers at Brown University have developed an interface that combines elements of these two topics, but this was not empirically evaluated. My suggestion for future research is to continue this avenue by rigorously evaluating and comparing their interface to the conventional one used by 3D modeling software.

Categories and Subject Descriptors: I.3.6 [**Computer Graphics**]: Methodology and Techniques – Interaction Techniques; H.1.2 [**Models and Principles**]: User/Machine Systems – Human Factors

Additional Key Words and Phrases: 3D User Interfaces, 3DUI, Direct Manipulation, Human Computer Interaction

1. INTRODUCTION

3D animation and modeling packages are a popular form of computer-aided design (CAD) software used to create complex, interactive 3D scenes. This software has allowed for significant progress in many industries, including computer game design, architecture and medicine [Hinkley et al. 1994(b); Bowman et al. 2004; Jankowski and Hachet 2013]. Modern 3D modeling packages are very sophisticated software suites and are publicly available to amateurs and professionals alike.

While these systems have progressed significantly in terms of overall functionality, features and graphic processing [Oh and Stuerzlinger 2005; Bowman et. al 2006; Jankowski and Hachet 2013], the user interface (UI) has remained fairly consistent. All packages make use of 3D user interfaces (3DUIs), which are interfaces that allow the user to directly interact with and create objects in the 3D spatial context [Bowman et al. 2004]. Since their initial launch, all 3D CAD systems seem to display this 3D spatial context to the user in the same way. The standard convention is to display one perspective and three axial orthogonal views on the screen at all times (Figure 1) [Tory et al. 2006]. The user can then interact with the 3D objects in the scene directly, or by selecting an option from a toolbar of features. There is no literature available identifying exactly why the modeling suites favor this multi-view orthogonal and perspective convention over other alternatives [Herndon et al. 1992; Rizzo et al. 2005]. Furthermore, there has been no research into empirically evaluating whether this convention is the best technique to see and interact with the 3D scene in modeling software applications.

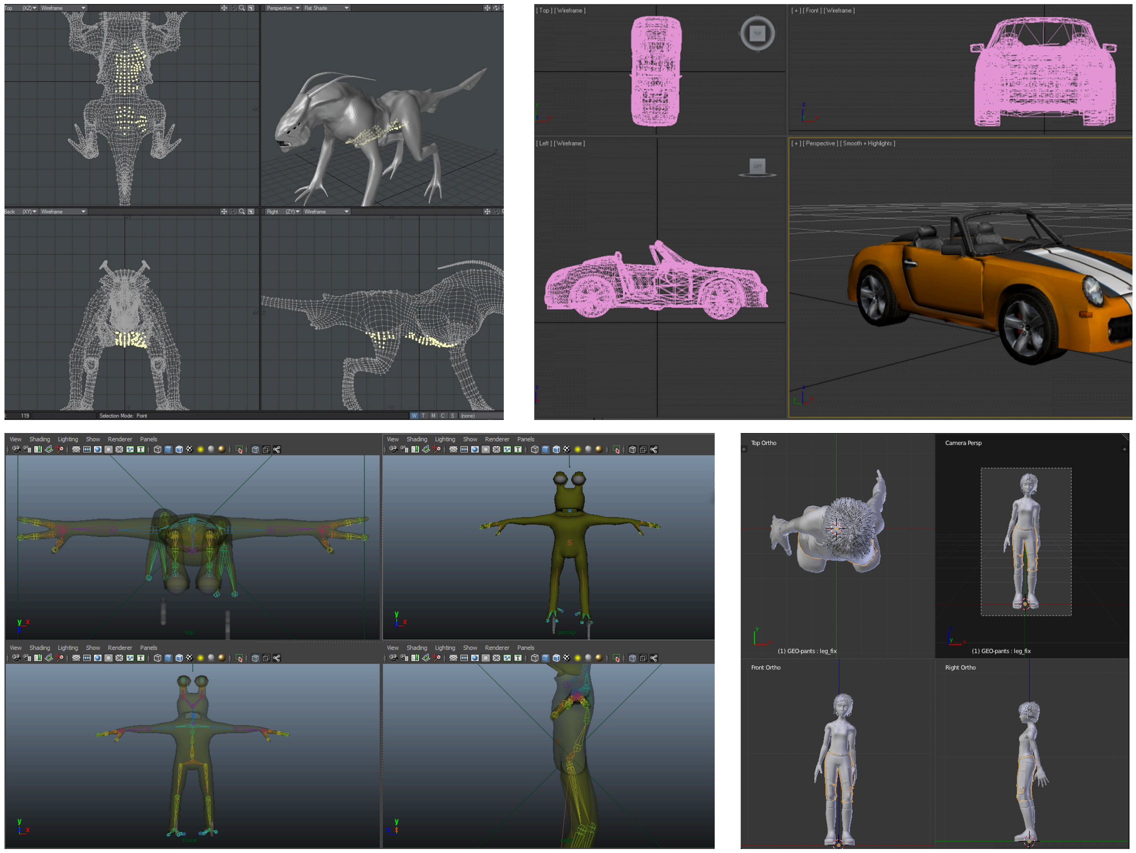

Fig. 1. This figure shows examples of models displayed in the conventional multi-view orthogonal interface in four popular 3D modeling and animation software suites [Autodesk 2015 (a); Autodesk 2015(b); NewTek Inc. 2015; Blender Foundation 2015]

One of the main challenges facing the UI design of 3D modeling packages is the physical technology. These programs are most prevalently used on desktop or laptop machines, which limits the user to 2D input (mouse) and output (display screen) devices to interact with a 3D scene [Herndon et al. 1992; Smith, Salzman, and Stuerzlinger 2001; Oh and Stuerzlinger 2005]. This is widely accepted as a difficult problem to solve [Carey et al. 1994]. While there is evidence to suggest that 3D input or output devices can be more effective in certain 3D scene manipulation tasks [Hinckley et al. 1994(a); Zaman et al. 2012], the current standard in industry is still 2D input and output devices [Jáuregui, Argelaguet, and Lecuyer 2012]. Thus, research into improving this specific area of 3DUI could have a significant impact on the industry.

There has been extensive research into the area of improving the conventional UI, but very little evaluation on the effectiveness of these improvements [Hubona et al. 1999; Bowman et al. 2004; Jankowski and Hachet 2013]. These gaps in the literature highlight the potential for improving the usability of the 3D scene manipulation present in current 3D CAD systems. They also show a definite lack of formal evaluations to determine empirical relative effectiveness between 3DUI techniques in this area.

This review critically examines 3D scene manipulation techniques in this context, focusing particularly on how to empirically evaluate and compare them. Section 2 identifies important concepts for 3DUIs for 2D input and output systems. Section 3 goes on to outline the different techniques for how to scientifically evaluate 3DUIs and common confounding factors that can affect these interfaces in particular. This leads on to Section 4 in which I will make draw on key studies mentioned throughout the review to make suggestions as to those areas most in need of further research and development. In support my prior arguments, my conclusions will function as a review of the knowledge gained by this survey.

2. 3D USER INTERFACES

While this review focuses on a specific subset of 3DUIs, it is helpful examine the topic more broadly to gain insight on what should guide the evaluation process. In this section I will touch on some of the key concepts of 3DUIs, and how they apply to 3D modeling software.

2.1 What makes an interface a 3DUI?

3DUIs by definition are UIs that allow users to interact directly with 3D objects in a computer simulated 3D environment [Bowman et al. 2004; Jankowski and Hachet 2013]. These interactions can be grouped into three types of tasks that all 3DUIs need to account for. I discuss these briefly below.

2.1.1 Scene navigation tasks

These are tasks relating to how the user manipulates their viewpoint within the 3D world; 3D environments are usually quite complex and cannot be understood and manipulated accurately from only one perspective [Tory et al. 2006; Jankowski and Hachet 2013]. An example of this kind of interaction in a 3D modeling context is changing the camera angles, zooming in and specifying the camera's position.

2.1.1 System control tasks

These refer to tasks that affect the power the user has over the system's behaviour. The 3DUI must enable and not hinder the user's interactions, and must feel as natural as possible. The user must feel completely in control of their 3D world, as any disconnect between the user's intentions and resulting actions has been found to trigger annoyance and loss of engagement with the application [Herndon et al. 1992; Jankowski and Hachet 2013].

2.1.1 Selection and manipulation tasks

These relate to how the user interacts with the 3D objects within the scene. These are predominantly object positioning, rotation and scaling tasks [Jankowski and Hachet 2013] and are fundamental to any 3D CAD software. In this context, the user must be allowed to complete these tasks as precisely and efficiently as possible [Hubona, Shirah, and Jennings 2004; Rizzo et al. 2005]. These are the primary function of modeling software, and are where the majority of the research in 3DUI for this software occurs.

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 that have been shown to be best for specific scenarios [Bowman et al. 2004]. This review focuses predominantly on the selection and manipulation tasks, as this is where the largest gap in evaluative literature lies.

2.2 Types of 3DUIs

There are two main types of 3DUIs, namely direct manipulation and spatial interaction. 3D modeling software takes the first approach, which transforms the users input by using a non-3D input tool directly into real time actions on the screen [Shneiderman 1983]. This concept was created to act as metaphor for real-world interactions by drawing parallels between the way you interact with objects in the system using your mouse, and the way you would physically with your hands in real life [Bowman et al. 2004]. Direct manipulation 3DUIs have been found to allow faster and more accurate selection and manipulation task completion, but are less immersive than spatial interaction interfaces [Herndon et al. 1992; Bowman et al. 2006].

Spatial input makes use of free-space 3D input devices and can be found in many gaming and virtual reality systems [Hinckley et al. 1994(a)]. The majority of research into the area of 3DUIs has been in this subset, and it has been found to be a very good approach to implement when navigation and understanding the 3D scene is the main goal of the application [Bowman et al. 2006; Jankowski and Hachet 2013]. However, the spatial input technique is less suitable for 3D CAD systems, because it suffers from significant precision errors [Hinckley et al. 1994(a)]. The 2D mouse still far outweighs these systems in terms of accuracy, speed and control when compared to the interaction devices of these systems such as the Microsoft Kinect and Nintendo Wiimote [Zaman et al. 2012; Jankowski and Hachet 2013].

3. EVALUATING 3DUI INTERACTIONS

Research into the 3D interaction field has for many years focused on creating new and innovative interaction devices and techniques. Researchers spent their time coming up with new methods to interact with 3D space, but didn't return to evaluate the quality of these innovations in terms of usability [Bowman et al. 2004; Domingues, Otmane, and Mallem 2010]. This has left the field with very little evidence as to the quality of existing 3DUIs. Furthermore, there are few concrete guidelines for how to effectively assess the usability of 3DUIs [Bowman et al. 2004; Rizzo et al. 2005]. Researchers have begun to apply methods developed for 2D and more generic graphical UIs. While this is an acceptable approach, there is no evidence that these methods are directly applicable to 3DUIs.

3.1 Evaluation Methods

Once a UI has been developed there are two main ways to quantitatively evaluate its effectiveness. The first is to compile a formative user evaluation [Bowman et al. 2004] in which users are required to complete a set of tasks that fully test doing scene navigation, object selection and manipulation, and user control using this UI [Rizzo et al. 2005]. The users' performance is measured according to a certain set of metrics (see Section 3.2.2).

The second quantitative method is a heuristic evaluation. This requires several usability experts to evaluate your UI design by comparing it to a set of design guidelines. This is done without user evaluations and is thus very useful in obtaining an objective analysis of the quality of the design. However, a heuristic evaluation is quite difficult to do for 3DUIs, as a standardized heuristic for this field has yet to be established [Bowman et al. 2004; Domingues, Otmane, and Mallem 2010].

Due to the subjective nature of human-computer interactions, it is important to consider the qualitative evaluations of a UI as well. This can give another dimension to the quantitative data by helping interpret the results more accurately [Jankowski and Hachet 2013]. Qualitative data in this context is usually gained from the participants after they have completed the formative user evaluation. Researchers will often allocate time to ask a few open-ended questions, do a one-on-one interview with the participant or ask the participant to explain their process to while completing each task [Bowman et al. 2004].

3.2 Gathering and Interpreting Results

When analyzing the results of the above evaluation methods, there are two sets of metrics applicable to 3DUI CAD systems – task performance and user preference metrics [Bowman et al. 2004; Rizzo et al. 2005]. These metrics must be analyzed together and take into account the caveats mentioned in the next subsection.

3.2.1 Task performance metrics

This is data gathered on how effectively the user can accomplish the tasks required of them in the user evaluation. These metrics are specific to the goal of the software system being evaluated [Jankowski and Hachet 2013]. In the evaluations of CAD 3DUIs this would be the speed and accuracy at which the users can complete their object selection and manipulation tasks [Hubona, Shirah, and Jennings 2004]. It is important to note that this metric does not account for how much the user enjoyed using the program, but rather how well they performed while using it. These metrics cannot be interpreted in isolation, as user preferences may significantly affect their task performance [Bowman et al. 2004].

3.2.2 User preference metrics

These involve the user-centric part of the user evaluation. They report on how easy the system is to use, how long it takes to learn how to use it and how satisfying it is to use, among other things [Bowman et al. 2004]. There are reliable questionnaires that researchers use to measure these outcomes, as well as more qualitative interviewing approaches [Bowman et al. 2004; Rizzo et al. 2005].

User preference metrics also provide insight on the presence and comfort experienced by the user. Presence refers to how “transparent” the UI feels to the user; the user should feel present within the virtual environment, as if they are interacting directly with the objects, and not through an interface [Bowman et al. 2004].

Comfort is similar, and applies to how at ease the user is with the interactions with the software. Many immersive 3DUIs can cause a form of motion sickness, which brings down the user’s overall feelings of comfort [Bowman et al. 2004]. While this is not an issue usually faced by 3D modeling software, it is important to monitor overall comfort. If the application strains, confuses or annoys the user in any way, the level of comfort can decrease and affect the overall results of the study [Herndon et al. 1992; Jankowski and Hachet 2013].

3.3 Caveats

In any experimental evaluation there are certain confounding factors that one must account for. Since the assessment of 3DUIs is predominantly based on user evaluations, a number of human factors arise [Bowman et al. 2004; Rizzo et al. 2005].

The general population’s abilities to interact with 3DUIs are unpredictable. People from all backgrounds vary greatly when it comes to inherent skill, learning ability, and previous familiarity with these systems. Gender has been found to play a significant role in a person’s ability to interact with 3D virtual environments. Studies have shown that males have significantly higher visuospatial abilities than females [Tory and Möller 2002; Seurinck et al. 2004; Cesare Cornoldi and Tomaso Vecchi. 2004; Hugdahl, Thomsen, and Ersland 2006].

A notable 3DUI study attempted to account for this by measuring visuospatial ability using the Mental Rotations Test (MRT) [Rizzo et al. 2005]. This study found that males performed significantly better than females on the MRT. However, there were no significant differences between the genders while performing the 3D selection and manipulation tasks using a 2D mouse. This suggests that visuospatial ability moderates, but doesn't directly predict 3D manipulation performance with a mouse. Culture and/or educational background were 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 of a 3DUI can have a noteworthy influence on the user's qualitative and quantitative results in the study. If the interface is too confusing, the user can quickly lose interest and become frustrated [Herndon et al. 1992]. This draws from the fundamental 3DUI concepts of direct manipulation and system control, where the user should always feel in complete control of the actions executed through the interface [Shneiderman, 1988; Jankowski and Hachet 2013]. A 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 [Smith, Salzman and Stuerzlinger 2001; Oh and Stuerzlinger 2005; Tory et al. 2006].

The final potentially confounding factor present in a number of 3DUI experiments is participant fatigue. In order to critically evaluate each interaction task for an interface, experiments can take a long time [Jankowski and Hachet 2013]. Participants' task performance and user preference metrics both suffer if they are required to take part in experiments that are "too long" [Bowman et al. 2004]. It is advised that experiments are kept as short as possible, and in the event of having to do multiple tests, that the participants be given a break in between. The studies that evaluate the differences between two or more systems usually use the latter tactic, as these require participants to do the same tasks multiple times [Bowman et al. 2004; Rizzo et al. 2005].

4. CURRENT AND FUTURE EVALUATION WORK

In this section I critically discuss five publications that empirically evaluate mouse-based 3D scene manipulations in various scenarios. I summarize their strengths and weaknesses, and what their contributions mean for the future research in this area. I then suggest a future project that would fill the gaps I have found in the current literature.

All these studies (summarized in my appendix) follow a within-groups repeated measures design. This can suffer from the participant fatigue effect mentioned in the above section. The researchers in these studies specifically mention keeping the experimental time as short as possible, giving participants ample rest time when required.

The publications I found all focused on evaluating mouse-based 3D object manipulations in various contexts. I selected these studies as they specifically address the area of object selection and manipulation tasks, which are crucial to 3D CAD software interactions. They required participants to select, position, resize, and/or rotate objects using the mouse-based system. They then evaluated the participant task performance on speed and/or accuracy. Most of the studies evaluated user preference metrics as well, with the exception of Hubona, Shirah and Jennings (2004), who focused purely on a qualitative analysis.

These evaluations all attempted to practice a rigorous scientific method, however they have certain weaknesses in their choice of participants. Firstly, the sample sizes for the majority of these experiments are quite low, with Oh and Stuerzlinger (2005) and Jáuregui, Argelaguet, and Lecuyer (2012) having only 10 and 12 participants respectively. Such a small sample size is useful for a pilot study to show that a research area shows promise, but the results cannot be used to infer anything about the general population. The second issue with the method of participant selection in these studies is the lack of standardization. Only Rizzo et al. (2005) intentionally balanced the genders in each experiment they conducted. They were also the only study I found that acknowledged and accounted for the effects of varying educational and cultural backgrounds. Rizzo et al. (2005) found that male and female performance in 3D interaction tasks are not significantly different, which means that the gender imbalances in the other studies may not have affected the results at all. However, it would have been useful to have data from the other studies supporting this claim.

These studies are all helpful in understanding the problems faced by 3DUI researchers today. Due to their vastly different participant groups and overall research focus, their results are largely incomparable. However, there are two main findings that are applicable to future 3DUI research specifically in the area of improving the interfaces used by modeling software:

- Users find it difficult to perceive depth in 3D virtual environments. Using effects drawn from real-world interactions such as shadows and occlusion are significantly helpful reducing inaccurate depth perception [Hubona, Shirah, and Jennings 2004; Oh and Stuerzlinger 2005; Jáuregui, Argelaguet, and Lecuyer 2012].
- Interactions confined to a 2D plane are very helpful in ensuring quick, accurate selection and ordering tasks [Smith, Salzmann, and Stuerzlinger 2001].

After my review of these studies, I would suggest that future research into the area of 3DUIs in CAD systems incorporate these two topics. In my opinion, effective use of depth cues together with 2D movement constraints could have a significant improvement upon the current modeling interface convention.

Research on incorporating these two topics has already been done by researchers at Brown University [Herndon et al. 1992; Zeleznik, Herndon, and Hughes 2007]. They proposed a new interface style where the 3D scene is enclosed by a box, and the 3D object's orthogonal projections are displayed on the walls of the box (see Figure 2). These projections are called shadow widgets and can be manipulated along their 2D projected plane. Thus the user can manipulate both the 3D objects in a more conventional manner, as well as its 2D shadow projections.

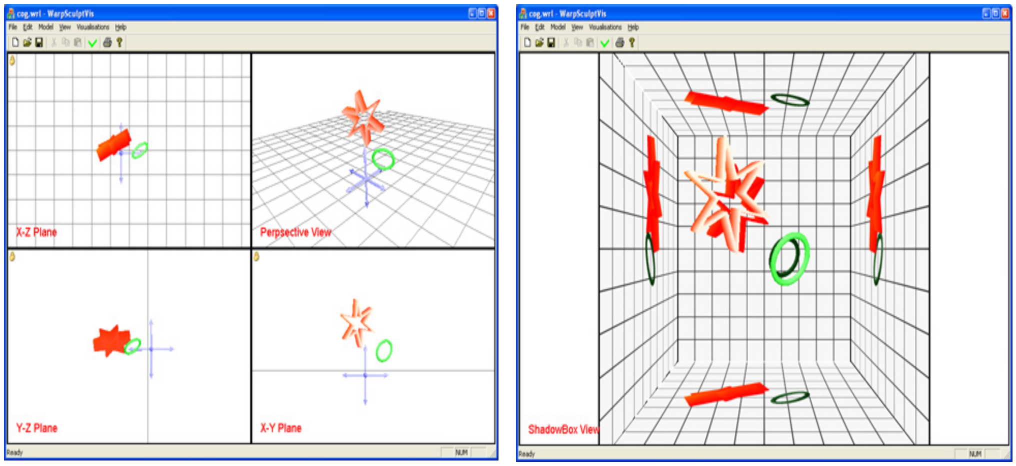

Fig 2: Conventional interface (left) and "shadowbox" interface (right) mockup

This method has been critically analyzed and was used by the researchers themselves to illustrate its effectiveness as an alternative to the current convention. However, no rigorous user evaluation was done to assess the qualitative and quantitative aspects of this interface. For future research, I suggest that this interface is revisited and empirically evaluated alongside the current conventional interface. From my review of the literature, I believe that if evaluated properly, this could shed new light on how 3D modeling software interfaces should be designed.

5. CONCLUSIONS

This review critically examined 3D scene manipulation techniques in the context of modern 3D modeling software. The focus was on how to approach empirically evaluating and comparing interfaces, and finding potential alternatives to the current modeling 3DUI convention.

I researched the broad concepts of 3DUIs, and then examined these in relation to CAD software for 2D input and output systems. I then identified how to scientifically evaluate 3DUIs, and found that as yet there is no standardized approach [Bowman et al. 2004]. This significantly complicates the evaluation process, specifically when attempting to compare two separate studies. My focus then shifted to five publications that attempted to evaluate mouse-based 3DUIs, and I found that their results were significant, but could not be safely generalized to the greater population.

These studies did identify two possible avenues for future evaluative research, namely depth cues and 2D manipulation constraints. I discovered that researchers at Brown University have already designed a "shadowbox" interface that intuitively combines these two concepts [Herndon et al. 1992; Zeleznik, Herndon, and Hughes 2007], but that they have not scientifically evaluated this interface.

In conclusion, I suggest revisiting the "shadowbox" interface designed by Herndon et al. (1992), as this seems like a very promising alternative to the conventional CAD 3DUI. Special care must be taken to ensure that the evaluation is designed in such a way that the results are valid for the general population.

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APPENDIX

Table 1: Summary of experimental evaluations of 3DUIs focusing on 2D mouse interaction devices

Experiment	**Focus**	**Tasks**	**Subjects**	**Task Performance Metrics**	**User Performance Metrics**
Hubona, Shirah, and Jennings 2004	Casting shadows to increase depth perception	Relative object positioning, Object resizing	Females: 14 Males: 16 Average Age: 35	Speed, Accuracy	None
Oh and Stuerzlinger 2005	Using occlusion depth techniques to improve object positioning	Relative object positioning	Females: 4 Males: 6 Age: 20-35	Speed	Preference
Rizzo et al. 2005 experiment 1	Identifying evaluation heuristics for 3DUIs by comparing 2 interaction devices	Object selection and release, Relative object translation, Object rotation	Females: 10 Males: 10 Average age: 29	Speed, Accuracy	Ease of learning, Cumbersomeness, Fatigue, Comfort, Preference
Rizzo et al. 2005 experiment 2	Identifying evaluation heuristics for 3DUIs by comparing 2 interaction devices	Object selection and release, Relative object translation, Object rotation	Females: 12 Males: 12 Average age: 26	Speed, Accuracy	Ease of learning, Cumbersomeness, Fatigue, Comfort, Preference
Smith, Salzmann, and Stuerzlinger 2001	Mapping 2D physical constraints to moving objects in a 3D environment	Relative object positioning	Females: 2 Males: 13 Average Age: 23	Speed, Accuracy	Preference
Jáuregui, Argelaguet, and Lecuyer 2012	3D cursor visualization and motion parallax to increase depth perception	Object selection Object ordering	Females: 2 Males: 10 Age: 22-34	Speed Accuracy	Preference, Comfort