Virtual Task Environments Factors Explored in 3D Selection Studies

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Abstract

In recent years, there has been a race among researchers, developers, engineers, and designers to come up with new interaction techniques for enhancing the performance and experience of users while interacting with virtual environments, and a key component of a 3D interaction technique is the selection technique. In this paper, we explore the environmental factors used in the assessment of 3D selection methods and classify each factor based on the task environment. Our approach consists of a thorough literature collection process, including four major Human-Computer Interaction repositories—Scopus, Science Direct, IEEE Xplore, and ACM Digital Library and created a dataset of a total of 909 papers. Drawing inspiration from the parameters outlined by Laviola et al. we manually classified each of those papers based on the task environment described in the papers. In addition, we explore the methodologies used in recent user studies to assess interaction techniques within various task environments, providing valuable insights into the developing landscape of virtual interaction research. We hope that the outcomes of our paper serve as a valuable resource for researchers, developers, and designers, providing a deeper understanding of task environments and offering fresh perspectives to evaluate their proposed 3D selection techniques in virtual environments.

Index Terms: Human-centered computing—Virtual Reality—Augmented Reality—3D User Interfaces; Human-centered computing—Selection—Virtual Task Environments

1 Introduction

The advancements in Virtual Reality (VR) and Augmented Reality (AR) systems have led to an increased focus on the overall perception and satisfaction of users. This also involves interactivity, e.g., the dynamic exchange of information between the user and the VR system, allowing users to interact with and manipulate objects or elements in the virtual space. As a result, one of the major research topics of 3D user interfaces (UI) focused on developing novel 3D interaction techniques, aiming to interact with and manipulate virtual objects seamlessly and intuitively.

Researchers developed novel interaction techniques for 3D UIs to address specific challenges and limitations associated with existing methods such as raycasting and virtual hand [9]. While these common techniques are widely used, they have limitations in terms of addressing diverse user needs, providing precision and accuracy, and addressing challenges in interaction scenarios. Thus, 3D UI studies started to propose novel interaction methods designed for Virtual Reality (VR) or Augmented Reality (AR) environments, each addressing specific challenges and offering trade-offs in terms of time, accuracy, and precision or offering improvements in user experience, efficiency, and adaptability to different virtual environments. Consequently, researchers, practitioners, and designers continue to propose novel 3D interaction techniques based on various aspects, including input devices, virtual environments, and task complexity, e.g., [86, 115, 150, 213].

One crucial aspect of interaction techniques is 3D selection, which is closely intertwined with effectively navigating and manipulating objects within a 3D space. Selection is considered one of the major methods of interaction with physical and virtual environments [115]. According to LaViola et al.'s 3D User Interfaces book [115], the selection is defined as one of the four "*canonical tasks*" for manipulation, which is a sub-part of the interaction techniques. Here, we define 3D selection in virtual environments as the action of identifying, highlighting, or designating specific items or elements within a 3D space.

The virtual task environment plays a crucial role in 3D selection studies, enabling the exploration of innovative techniques for challenging parameters such as occlusion and density. Additionally, the field of VR & AR has undergone significant advancements in the past 25 years since the last comprehensive paper on virtual task environment factors for 3D selection [180]. The rapid evolution of VR technologies and systems has introduced novel features, improved graphics, and enhanced interaction capabilities.

Given these recent developments in the past 25 years, there is a need to update the literature on virtual task environment factors to align with the current state-of-the-art systems since the variation of task environments in recent studies on 3D selection techniques has not been thoroughly examined. With the advancements in VR & AR systems, there is potential for the development and evaluation of new techniques in diverse task environments. An updated review will not only reflect the present capabilities of VR but also provide valuable insights for designing experiments that accurately represent the dynamic and sophisticated nature of today's virtual task environments. An elaboration on the classification of the virtual task environment factors that are used to evaluate the proposed techniques can support researchers, developers, and practitioners in creating efficient task environments. This can reveal the potential of the evaluated technique under different task environment factors.

In this paper, we explored different virtual task environment evaluation factors used in 3D selection studies and discussed them. We also extended the existing literature by either sub-categorizing environment parameters or proposing novel parameters. We hope that our results in this paper can be used to determine and design the virtual task environment to evaluate their proposed 3D selection method.

2 Previous Work

The previous studies surveyed, reviewed and analyzed 3D selection techniques as well as 3D interaction techniques. One of the first studies that reviewed the selection techniques is Hand's survey on 3D interaction techniques [86]. In that paper, Hand focused on different interaction techniques designed for mouse and 3D input devices. In a latter study, Bowman et al. [40] classified 3D selection techniques by different tasks. Researchers grouped occlusion, object touching, pointing, and indirect selection under the indication of objects. Dang also surveyed and classified 3D selection techniques based on 3D cursor [62].

In recent years, surveys on 3D interaction techniques mostly focused on immersive environments and VR & AR HMDs. In Arelaguet and Andujar's survey [9], along with 3D object selection

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method classification and human models used for evaluation, the authors examined the factors influencing user performance. They explored target geometry, object distance and area of reach, and object density topics, which are related to the task environment parameters. In Mendes et al.'s survey [150], the authors focused on 9 degrees of freedom manipulation techniques. They analyzed different trends in interaction and object manipulation in virtual environments.

Poupyrev et al. [180] described task parameters as independent variables that affect the users' performance during the selection process. Later, LaVioala et al. [115] used the identical set of parameters as in Poupyrev's work to define task parameters that are used for design dimensions in 3D UIs. These parameters are distance and direction to the target, target size, the density of the objects around the target, the number of targets to be selected, and target occlusion. The authors also briefly mentioned the application- and domain-specific approaches. In this paper, we will use this classification to further extend the literature on virtual task environment parameters.

Other papers surveyed 3D interaction techniques, such as Subramanian and IJsselsteijn [217] and Zhi et al. [281], but all these papers were focused on either 3D interaction techniques or 3D selection techniques, but not the environment parameters.

3 METHOD

On July 17th, 2023, we searched four major Human-Computer Interaction (HCI) repositories: Scopus, Science Direct, IEEE Xplore, and ACM Digital Library. In Scopus, our query [ALL("3D selection") AND (ALL("Virtual reality") OR ALL("Augmented reality"))] within the period 1997 to 2023, resulted in the identification of 442 research papers.

In Science Direct, using the query ["3D selection" AND ("virtual reality" OR "augmented reality")] within the timeframe ranging from 1993 to 2023 returned 31 research papers.

The search query [All: "3d selection"] AND [[All: "virtual reality"] OR [All: "augmented reality"]] in the ACM digital library between 2007 and 2023 gave us a total of 81 research papers.

Within IEEE Xplore, we searched for papers using the query ("All Metadata": 3D selection) AND (("All Metadata": "virtual reality") OR ("All Metadata": "augmented reality")). This search, covering the years from 1993 to 2023, gave us 369 papers.

We deliberately and strategically selected broad search terms for these queries. Using a wide net of keywords in our keyword selection, we aimed to maximize coverage and minimize the risk of overlooking any pertinent research papers on the topic of 3D selection.

4 RESULTS

Our queries resulted in a total of 909 papers (81 ACM Digital Library + 355 IEEE Xplore + 442 Scopus + 31 Science Direct). We manually reviewed and analyzed each of these papers and removed 495 of them that were not about 3D selection in interaction methods (220 of them from IEEE Xplore, 12 from Science Direct, 260 from Scopus, and 3 from the ACM Digital Library). We also disregarded 31 survey papers (21 papers from Scopus, 1 paper from Science Direct, 7 papers from IEEE Xplore, 2 papers from ACM Digital Library), 3 lecture notes from Scopus and ACM Digital Library, 1 editorial and 1 book chapter from Scopus and Science Direct respectively and 11 papers in other languages rather than English (3 papers from Scopus, 6 papers from IEEE Xplore and 2 papers from ACM Digital Library). We also excluded 62 papers that did not explain the task environment used to evaluate the interaction technique (8 papers from ACM Digital Library, 12 papers from Science Direct, 20 papers from Scopus, and 22 papers from IEEE Xplore) and 1 paper with no change in selection techniques from ACM Digital Library. We also dismissed 11 papers (4 papers from ACM Digital Library and 7 papers from IEEE Xplore) with no task description. We came across 17 papers that were present in two different repositories. Given the potential for redundancy and duplication of research findings, we decided to disregard these 17 papers. A total of 632 papers, 26 papers from Science Direct, 325 papers from Scopus, 23 papers from the ACM Digital Library, and 258 from IEEE Xplore, respectively, were disregarded in this study.

We only considered the papers that were archived by the above-mentioned repositories. In other words, we did not include posters, workshop papers, and other materials that might be extended to a full article, as the final results of the study might vary.

5 TASK ENVIRONMENT PARAMETERS & CLASSIFICATION

We systematically categorized a total of 277 papers related to 3D selection techniques, primarily based on the task environments in which these techniques were applied. To provide a clear overview of our findings, we present our findings in 3 tables.

We first present a brief summary of papers that align with the task environment classification outlined by LaViola et al. [115] in Table 1.

We also extend existing research by classifying papers that combine two or more task environment parameters to evaluate 3D selection techniques. A summary of these additional categories is shown in Table 2.

In addition, we added five new categories to our classification scheme to broaden the scope of the literature. These new categories were based on emerging paradigms and novel approaches in 3D selection research. A comprehensive summary of these new categories, along with their corresponding references, is presented in Table 3.

5.1 Task Environment Parameters Classification based on Current Literature

This section examines papers that fit the description of task environment parameters outlined by LaViola et al. [115].

5.1.1 Distance and Direction to the Target

The first task environment described in LaViola et al.'s [115] book is the distance and direction to the target. Here, the target distance refers to the distance variation between the target and the other surrounding objects. In some research papers, the target distance refers to the distance between the camera, i.e., the user's position, and the target. On the other hand, target direction refers to the orientation or direction between the target and the other surrounding objects. Similarly, the target direction can indicate the direction between the camera, i.e., the user's position, and the target position in the 3D environment. Target distance and direction have a significant effect on users' performance in 3D selection studies, when the distance between the user and the target object increases, accurate target selection becomes more difficult due to the smaller appearance of the target object. Within this category, we examined papers that varied the distance between the target and surrounding objects, as well as the orientation of objects in relation to the target. In total, we found 117 papers in this category.

Specifically, papers such as [12,30,32,139,193,258,266], investigated the impact of altering the spatial separation between the target and other objects in the virtual environment. These papers aimed to investigate how such variations affect performance metrics such as target selection accuracy, task completion time, and the selection strategies employed.

Similarly, papers, such as [63,190,224], modified the orientation of objects relative to the target in the virtual environment, examining how objects facing towards or away from the target influenced target selection accuracy, task completion time, and the observer's approach to the task.

In several papers, including [24,26,171,204] researchers explored the performance and usability of different target selection techniques

Table 1: Virtual task environment classification outlined by LaViola et al. [115].

Parameters	Description	References
Distance & Direction to the target	Authors vary distance and direction to the targets to understand what effects it has on the user's perception, accuracy, and time.	[2, 5, 6, 12–14, 18–20, 22, 23, 26–36, 41–44, 44, 56, 58, 63, 65, 70, 74, 78, 84, 87, 88, 90, 94, 98, 106, 108, 113, 114, 117, 118, 122, 123, 126, 128, 130, 131, 135–139, 142, 144, 148, 151, 153, 154, 158, 165, 169, 171, 178, 185, 187, 190, 193, 209, 210, 221, 223, 224, 226–229, 238, 243, 244, 253, 255, 258, 259, 266, 270, 271, 276, 282, 283, 285, 286, 288]
Target size	Researcher investigates the effect on 3D selection performance and task completion time changes in the target's width, height, and size.	[5, 17, 21, 24, 25, 30, 33, 63, 71, 81, 101, 107, 112, 119, 121, 125, 133, 134, 140, 147, 152, 167–169, 176, 183, 191, 194, 204, 208, 215, 232, 247, 251, 252, 254, 263, 267–269, 280, 284]
The density of the objects around the target	Authors evaluated the effects of object density on 3D selection performance by designing virtual environments with a high concentration of objects in proximity to the target.	[7, 21, 24, 25, 38, 39, 49–54, 59, 60, 67, 77, 82, 92, 97–100, 117–119, 121, 129, 133, 134, 148, 149, 155, 156, 158, 159, 162, 170, 173, 176, 177, 184, 188–190, 192, 196, 205, 214, 232, 235, 238–241, 244, 247, 248, 252, 254, 255, 260, 264, 267, 268, 272, 273]
Number of targets to be selected	The impact of object size, dimension, and quantity on user selection performance was investigated by researchers in scenarios where users were tasked with choosing a specific number of unique objects from a set of similar objects.	[162, 165, 244]
Target occlusion	Researchers designed the environment in an occluded manner and varied the degree of occlusion, such as the size and location of the occluding object, to measure how these factors affect task completion time, error rate, and user selection preferences.	[1, 2, 6, 10, 11, 25, 37–39, 51, 57, 59, 68, 69, 77, 87, 92, 98, 99, 103, 118, 119, 133, 134, 140, 148, 149, 151, 152, 155, 160–162, 165, 170, 174–176, 178, 188, 192, 194, 199, 206, 207, 214, 222, 235, 238–240, 244–248, 255, 263, 267–269, 273, 275, 280]

such as Raycasting and Virtual Hand with variations in target objects' distance and direction and reported the shortcomings of these techniques. One such notable shortcoming is that user performance decreases for small and distant objects with the raycasting interaction technique.

Overall, in the evaluation of novel 3D selection techniques within 3D UIs, the distance and direction to the target have emerged as crucial factors.

5.1.2 Target Size

Within the scope of this category, we identified 46 papers that centered their investigation on the effects of varying target sizes. In these papers, the authors varied the dimensions of a target, e.g., the target's width, height, and depth. Target size plays an important role in 3D selection studies within a virtual environment. These papers also contributed to a comprehensive understanding of how these size-based variations impact the effectiveness and efficiency of 3D selection techniques, since a target's size directly impacts the precision and accuracy of selection, with larger targets typically facilitating easier and more reliable interactions. However, higher degrees of precision lead to increased error rates and longer selection times. Considering the lack of physical support in mid-air interaction, the evaluation of the selection technique in terms of precise and accurate interaction for small targets plays a crucial role in understanding its efficiency.

Furthermore, our survey revealed six studies [25, 63, 167, 215, 263, 284] that considered target shape as a factor to evaluate 3D selection performance. Through the examination of aspects such as whether the target shape is round or square, these studies extended the exploration beyond simply examining the size of the target.

In a 3D selection task user's selection accuracy, speed, and overall experience are greatly influenced by the target object's characteristics. It is important to find the right balance between different target sizes and shapes to create an instinctive and efficient virtual environment.

5.1.3 The Density of the Objects Around the Target

Density refers to the concentration or amount of objects or elements within a given space. It is a measure of how crowded or compact the objects are in the virtual scene.

In this category, researchers have designed virtual environments with variable object density near the target to evaluate 3D selection techniques. In these studies, the researcher considered attributes of surrounding objects, such as their quantity, classification, dimensions, and spatial arrangement. A total of 65 papers investigated the impact of object density on task performance, exploring how changes in the number and arrangement of peripheral objects affect target detection accuracy and task completion time.

Several studies, including [189, 235, 264], also reported that increased object density can result in higher cognitive load as users navigate the crowded environment to identify and select the target. With the increased density around the targets, while participants' decision-making duration and the likelihood of errors were increased, their overall user experience decreased.

A densely populated environment can require more precise movements from users to avoid inadvertently selecting the wrong object. This increased demand for precision can lead to increased mental and physical effort, potentially resulting in user fatigue during the experiment or even after the experiment, which was observed by [134, 155, 238, 247, 267].

Overall, research has examined how object density in virtual environments affects task performance, revealing that higher densities can increase cognitive load and decrease user experience, resulting in fatigue in users as they navigate crowded scenes and need to be precise.

5.1.4 Number of Targets to be Selected

LaVioala et al. [115] described this factor as a task where users have to select a fixed number of unique objects among similar objects. We identified three [162, 165, 244] such papers that evaluated 3D selection methods in a virtual environment with a fixed number of target objects. These studies investigated the impact of various target object attributes, such as object color, size, and shape, on user performance. These virtual environments were designed to challenge users with the task of correctly identifying and selecting a set number of unique objects from a larger set of objects categorized by variations in size and dimension. This allowed researchers to investigate user interaction performance in situations that focused on the sequence and the number of target objects to be selected.

5.1.5 Target Occlusion

”Target Occlusion” in virtual environments refers to when an object in 3D space is partially or completely hidden or obstructed from view by another object. This can occur when one object is positioned in such a way that it blocks the user's line of sight to another object that they are trying to interact with.

We found 65 papers that used target occlusion to evaluate the 3D selection technique. These studies introduced occluded targets in their user study, as well as the characteristics of that occlusion, such as partial or full, e.g., [39, 119, 148, 275]. The researchers investigated the impact of occlusion on task performance, measuring factors such as completion time, error rate, and other performance metrics. By manipulating the degree of occlusion, including the size and location of the occluding objects, researchers explored how these factors influence task performance.

Overall, occlusion can hinder users' ability to assess the spatial relationships between objects. Understanding the relative positions of objects is crucial for effective interaction, and occlusion can disrupt this understanding, potentially leading to inaccurate selections and interactions.

5.2 Extending the Literature

In this subsection, we categorized papers that combine two or more existing task environment parameters and created a testbed for 3D selection techniques. These testbeds are also frequently used in 3D selection technique papers and highlighted by researchers. Thus, we also analyzed them here to extend the existing literature on task environment parameters.

5.2.1 Application Specific Environments

In this category, we focus on papers that used an application to evaluate the proposed 3D selection technique. In the virtual environment, the positions, sizes, orientations, and other environmental factors of the objects were varied to evaluate the technique. We found a total of 23 papers on application-specific approaches.

In these studies, users were not only performing a task; they were active participants who explored the prototype of the potential application. Through this engagement, users gain a tangible sense of how the virtual space would appear in the real application, enabling them to make informed decisions regarding object selection. In some of these studies, participants navigated within virtual environments and viewed the objects from different angles and perspectives, allowing them to get a sense of how the space would also look and feel in real life to select them.

5.2.2 Depth

Target depth in virtual environments refers to the spatial interval that spans from the user to a specific point of interest (target), containing the foreground, middle-ground, and background of the scene. It affects how the object is perceived, including size, location, and movement. Among the selected papers, 44 of them include depth as an evaluation factor in their design, highlighting its importance.

Depth variations introduce an additional layer of complexity to the 3D selection process. Users must not only consider lateral positions but also factor in the depth dimension, creating a heavier cognitive load. This can increase decision-making time as users mentally compute the relative distances between objects and their spatial relationships [122, 157, 230, 280].

Design considerations play a significant role in optimizing the effect of depth on 3D selection. Proper cues, shading, lighting, and visual feedback can enhance users' depth perception and assist in making accurate selections. The strategic placement of objects can ensure that important targets are within comfortable reach, minimizing the challenges posed by extreme depth differences [31, 183, 192, 218, 221].

Although this category is related to target distance and direction, we consider depth as an additional task parameter due to its frequent emphasis by researchers in the mentioned studies, and the authors indicate that they varied the target *depth*, not direction.

5.2.3 Targets Inside a Volume

In 3D selection studies, the idea of interacting with objects contained within prism-shaped volumes, such as cuboid volumes, is a unique area of interest. This involves scenarios where the target objects are positioned within defined spatial boundaries, or volumes, adding an extra layer of complexity to the selection process. Among the 277 papers, six focused on user studies involving target placement inside a volume, where users were instructed to select targets. Within these papers, Deng et al. [68] examined user performance and perception in virtual environment selection tasks, while Cordeil et al. [61] investigated selection accuracy and speed within a cuboid volume. Tran et al. and Marquardt et al. [145, 233] explored the impact of virtual-arm representation and collision interactions on user performance and perception, comparing confined and open space environments. These studies examined the influence of dense target placement in confined spaces on user perception and accuracy.

5.2.4 Menus

Researchers have explored the use of 2D graphical menus as a familiar and successful approach to evaluate 3D selection techniques in a virtual environment. We found a total of 14 studies that use menus as a virtual task environment.

Alex et al. [4] and Kapinus et al. [104] conducted comprehensive investigations on body-referenced graphical menus in virtual environments. Other studies examined shake menus [256, 257], handy menus [127], and peripheral menus [266], using various forms (linear and radial) and selection techniques. Additionally, studies such as [46, 66, 120, 197, 236] assessed task completion time, error rates, and user preferences for different menu-based selection techniques. Researchers introduced variations in menu elements, including size, distance, and density, to create diverse new virtual environments.

Graphical menus are widely used and evaluated in desktop applications and also integrated into immersive virtual environments. We view menus as an extension of the literature because researchers use them to test how people select things and see how making changes to menus affects user's selection process/performance in virtual reality.

5.2.5 Keyboard

In this category, we examined the papers that used either a physical keyboard or a virtual (i.e., soft) keyboard interface to evaluate the 3D selection technique. We found nine papers that used a keyboard to evaluate 3D selection techniques. The main goal of these studies is to evaluate the effectiveness of the selection technique used in the *typing* context. In these papers, participants used the keyboard to input commands and interact with target objects, which could include text, numbers, images, or 3D models. The studies varied factors such as target direction, distance, and key sizes during the selection process.

5.2.6 Pick and Place Task

Pick and place tasks include the requirement to set specific criteria and setups for users transferring things between predetermined places. These parameters contain the object's spatial coordinates, its orientation, and the intended target location where the object is to be placed. Seven papers [47, 47, 83, 109, 110, 182, 242] used pick-and-place task as a framework to evaluate the effectiveness of 3D selection techniques. These studies changed the experimental setup by introducing alterations in the tasks related to picking up and putting down objects in the 3D space, rather than executing the same action. These changes consist of an intentional modification of key factors such as the size of the objects, the direction, and the spatial separation between the origin and destination during the implementation of the task. The researchers adjusted these parameters to investigate the connection between the characteristics of objects, conditions of the task, and users' performance.

Table 2: Virtual task environment classification in 3D selection studies extending the existing literature.

Parameters	Description	References
Application Specific Environments	VR systems were incorporated by researchers to create 3D selection VEs, allowing users to explore virtual space, view objects from various angles, and modify object attributes like position, size, orientation, and environmental conditions to facilitate effective selection.	[3,15,16,64,76,80,85,89,116,156,164,172,195, 201,212,220,225,249,250,277,279,282,287]
Depth	In virtual environments, target depth refers to the spatial distance extending from the user to a designated point of interest, impacting the perception of objects in terms of size, location, and movement within the virtual space.	[8,18,19,26–31,33,46,55,72,88,101,122,133, 134,139,146,147,157,183,185,192,200,203, 218,219,221,226–228,230,234,236,237,274, 277,278,280,282]
Targets Inside a Volume	Numerous targets were placed within a volume to enhance object density and occlusion. These studies were conducted by researchers to examine how object density, occlusion, and target collisions within a confined space affect user performance and perception in virtual environments.	[61,68,145,202,232,233]
Menus	The use of 2D graphical menus as a selection method is being explored within 3D virtual environments. Researchers investigated the effects of different selection techniques on task completion time, error rates, and user preference by varying the elements in a menu, such as size, distance, or density, to create new virtual environments.	[4,46,66,104,120,124,127,181,188,197,236, 256,257,266]
Keyboard	A virtual environment was designed to evaluate the selection technique using a real or virtual keyboard. Users engage with target objects through a physical or virtual keyboard to assess the selection technique, involving participants using keyboard inputs to interact with various target objects such as text, numbers, images, or 3D models, where the selection of the next key requires movement towards a target direction at varying distances, potentially involving different keyboard configurations.	[32,36,79,102,143,261,262,266,278]
Pick and Place Task	The pick and place task involves defining the task environment for users to pick up and relocate an object, where parameters such as object location, orientation, target location, and object size, direction, and distance are varied during task performance.	[47,48,83,109,110,182,242]

In order to complete the pick and place task in a 3D virtual space, the user has to point, select, pick, and place the object in the destination point. The overall sequence of the pick and place task heavily depends on the accurate selection of the objects, which can be affected by factors including the target objects' size, distance, depth, and occlusion, or a combination of them. Thus, we categorize pick and place as a selection task in extending the literature subsection.

5.3 New parameters

We found that, in addition to the parameters mentioned above, to evaluate 3D selection techniques, researchers introduced new design parameters for their study. These parameters are different from those outlined by the LaViola classification [115] and are not a combination of them. In this section, we discussed these parameters in detail.

5.3.1 Adaptive Selection

Adaptive target selection in virtual environments involves identifying and selecting dynamic targets that may move, change shape or size, or appear and disappear over time. This specialized field emphasizes the dynamic nature of target interactions within virtual scenarios, offering an alternative to traditional *static* target selection paradigms. We found nine user studies highlighting the importance of considering the variation of target characteristics such as size, shape, color, and movement patterns in designing effective training and simulation programs for time-constrained and cluttered environments.

Studies [49,51,53,236] aim to explore the relationship between adaptive target characteristics and the effectiveness of selection processes. Unlike traditional selection models that consider targets as static with fixed properties, these studies acknowledge that real-world situations often involve targets that evolve dynamically. This requires users to make informed decisions under changing conditions. By adopting an adaptive approach that considers the temporal dimension of the selection process, the studies considered changes in target attributes over time, which can directly impact the user's ability to accurately and efficiently perceive, track, and select targets.

5.3.2 Height

Target height in virtual environment interaction refers to the vertical distance between the base level of the virtual environment and the top of the target, with the user as the reference point rather than the surrounding objects. Unlike the distance and direction to the target, the reference point to vary the object height was set as the base level or ground. For example, Mohr et al. [154] investigated the effect of targets placed with an offset based on the user's head height. Jackson et al. [97] evaluate users' selection preferences when selecting architectural design objects at varying heights.

The influence of target height on spatial awareness was explored in a study by Mohr et al. [154]. The study found that the manipulation of target height affected the accuracy of reach estimations, with reach being more significantly accurate for low target heights. This suggests that target height can impact spatial tasks, and the specific virtual body used may also influence performance. Therefore, considering target height as a new task environment parameter is important for understanding its effects on user interactions and task performance in virtual environments. Although there exists a correlation between height and distance and direction to the target, height adds a new paradigm to the user workload. For example, if an object's height is remarkably high, users will have to move their heads to bring it into their field of view, which can affect their selection accuracy. We found that the significance of height in the design of virtual environments has received limited attention in the literature.

5.3.3 Accessibility of Objects

The accessibility of objects/targets in virtual environments refers to the ease with which users can locate, select, and interact with them. This includes factors like target location, size, shape, and color, as well as the layout and design of the virtual environment. Particularly, in these studies, targets were not *occluded* but rather hidden or covered by other objects deliberately, which varies the mental model of the user, affecting their 3D selection performance. For instance, the participants had to remove an obstacle to reveal the spatial information of the target, such as its position. Three papers [73, 160, 238] investigated user perception, performance, and selection techniques in immersive virtual environments characterized by dense layouts. By including obstacle removal as a feature of the 3D selection task, the accessibility of objects was considered as a task environment parameter.

Intentionally manipulating accessibility as a task environment parameter enables researchers to explore the impact of changes in object visibility and interaction difficulty on the overall selection experience. The findings highlight the complex relationship between users' cognitive processes, spatial awareness, and motor skills in navigating targets with different levels of accessibility.

5.3.4 VR/AR Games

The core difference between VR/AR games and other parameters is that, in a game, a user's goal is to win, such as eliminating the competitor while following the game rules, whereas in other parameters user is doing a task following the experimenter's instructions without the explicit goal of winning. Moreover, most 3D selection studies were developed and evaluated in static or sparse environments. In contrast, games involve interaction with densely packed and dynamically changing objects.

VR/AR games offer opportunities to study user performance in various task environments and evaluate 3D selection techniques. These games use different 3D interaction techniques, providing a platform for researchers to explore user interactions with virtual environments and objects. Studies such as, [51, 52, 85, 111, 266] have investigated the challenges in object selection by comparing selection techniques.

VR/AR games stand out as a distinct parameter within virtual task environments, diverging fundamentally from conventional parameters such as target size, occlusion, and distance and direction to the target. VR/AR games are intentionally designed to actively involve and capture the players' attention. This intentional design creates an experiential dimension that exceeds the static or sparse nature commonly associated with traditional parameters. Further, in VR/AR games, users have to navigate and interact within dynamic, and often unpredictable, virtual environments where the goal is to win the game rather than just performing a task, compared to other environments factor. This dynamism establishes a clear difference, demanding users to adapt in real-time, facing challenges such as object occlusion, depth perception, and real-world interactions. This motivates us to consider VR/AR games as an independent design factor.

5.3.5 Immersive Data Visualization

Here, we define visualization as various visual elements that are used to display information in the virtual environment, and participants were asked to select information to evaluate the selection techniques.

Within our literature survey, we identified a total of 15 papers that used immersive data visualization as a task for evaluating 3D selection methods. In these studies, the prescribed task involves the selection of a virtual object integrated within the visualized data, thereby serving as the basis for evaluating the effectiveness of the respective selection methods. In addition, as the visualized data itself functioned as an essential task component in these investigations, we consider it as an individual parameter within the evaluation framework.

Another factor that influenced us to recognize this as a distinct task parameter is its unique impact on user interactions and decision-making processes. Traditional parameters often focus on physical aspects such as target size or distance, but the inclusion of immersive data visualization introduces a cognitive dimension. The representation of complex information in three-dimensional space not only influences how users perceive and interact with data but also poses new challenges for effective selection techniques. This emphasizes the nature of the relationship between data visualization and 3D selection techniques, exploring new challenges and opportunities presented when interacting with and selecting objects within immersive data-rich environments.

6 Discussion

In this paper, we explored the design considerations of evaluation factors within virtual environments, with a focus on how they affect the assessment of 3D selection techniques. The focus of our study, which was conducted within the larger field of 3D User Interface (3DUI) design, was the dynamic changes displayed by task environments in the context of 3D selection tasks. Our investigation was based on a collection of research papers that were carefully obtained from four research paper databases. These libraries were chosen for their importance in holding a multitude of materials related to 3D selection in Virtual Reality (VR) and Augmented Reality (AR) environments.

Previous surveys examined 3D selection techniques and 3D interaction techniques, such as 3D cursor for 3D selection by Dang et al. [62], task complexity by Bowman et al. [40] and user performance by Arelaguet and Andujar's survey [9]. Here, we aim to extend this literature to virtual task environment factors by LaViola et al. [115] to provide an updated classification, and thus improve the evaluation testbeds used to assess 3D interaction techniques.

Existing Literature and Task Environments The findings of this paper contribute to the existing literature on the use of virtual task environment parameters in 3D selection studies design, as originally defined by LaViola et al. [115]. These parameters, including distance and direction to the target, target occlusion, density, and target size, have been widely used by researchers in the field. We found that the distance and direction to the target category was the most frequently researched parameter, followed by target occlusion and density. An important finding of our paper is that researchers extensively explored how changes in spatial location and directional orientation affect user interactions within virtual environments. This emphasizes the importance of understanding the effects of target position and direction on the efficiency of 3D selection techniques.

The researchers also explored how changing the size of the target object compared to other objects affects the user's selection accuracy in virtual reality. For instance, when the target size is larger, it can become more user-friendly for selection, since users have a larger surface area to aim at. Additionally, researchers varied the density of objects around the target and explored how the presence and arrangement of nearby objects impact the selection process. In the more dense environment, 3D selection was more challenging. In occluded environments, they experimented with partial and fully hidden/occluded targets and observed how users approach those scenarios, how often mistakes are made, and how long it takes them to complete the task.

These findings provide valuable insight into which parameters researchers usually focus on when designing virtual task environments

Table 3: New Virtual task environment parameters in 3D selection studies.

Parameters	Description	References
Adaptive Selection	Adaptive target selection in virtual environments involves the dynamic process of identifying and selecting targets that exhibit changes in attributes such as movement, size, shape, appearance, or disappearance. These papers focused on users' quick and accurate identification and selection of targets, considering factors like target characteristics (size, shape, color, movement patterns), which significantly impact the selection process.	[17,49–53,132,236]
Height	Target height in virtual environment interaction corresponds to the vertical distance between the top of the target and the base level of the virtual environment, considering the user as the reference point rather than surrounding objects.	[97,154]
Accessibility of Objects	Accessibility of objects/targets in virtual environments is a complex factor that includes the target's location, size, shape, color, layout, and design of the virtual environment, as well as the user's expertise level and preference. Researchers investigated user perception and performance in selecting specific areas within large, dense, 3D-immersed virtual environments.	[73,160,238]
VR/AR games	VR/AR games offer players the opportunity to engage with virtual environments and objects using diverse 3D interaction techniques. They provide a valuable platform for researchers to investigate user performance in different task environments.	[51,52,85,111,266]
Immersive Data Visualization	Data visualization refers to the assortment of visual components employed to present information within the virtual environment, with the task focusing on selecting a virtual object that is part of the visualized data. The authors further assessed the performance of the selection techniques during task execution.	[45, 91, 93, 95, 105, 141, 163, 166, 179, 186, 198, 211, 216, 231, 265]

for evaluation purposes.

Extending Literature In addition to the task environment factors in LaViola et al. [115], recent studies also combined several factors and evaluated 3D interaction techniques for 3D UI design studies. Here, we explored the idea of combining several variables to produce varied and thorough evaluation scenarios. In particular, the incorporation of factors such as object density and occlusion in scenarios involving targets within volumes, as well as deliberate variations in target distance, direction, density, and size within menu-based task environments, augment the diversity of evaluated contexts. It is also important to mention that depth plays an important role in 3D selection techniques as well as 3D UI studies, and is frequently used as an assessment criterion in a large amount of research papers. Therefore, we separated depth from the existing classification and discussed it as a separate criterion.

In addition, we examined papers related to Fitts' Law [75] and relevant ISO 9241-411 [96] selection task to incorporate them into our classification. Although these tasks combine and vary target size and distance and are used for evaluating 3D pointing performance, we did not consider them as task environment parameters as one of their goals is to mathematically model human movement or analyze the speed-accuracy trade-off. Yet, we acknowledge their importance in evaluating 3D selection techniques.

Moreover, while certain task parameters may not be adjustable in some categories (e.g., keyboards), it is suggested to modify the factors that constitute that environment (e.g., target size and distance) within the task environment itself (e.g., keyboard) to vary task parameters during evaluation tasks.

New Parameters In this paper, we introduce additional new task environment parameters for evaluating 3D selection techniques. The motivation behind proposing these new parameters was to facilitate researchers to tailor their education to specific needs, contexts, or applications while improving their design. Since these new parameters focus on new environmental parameters and have different cognitive focuses, we examined them under distinct categories.

Our study introduces several new key parameters crucial for understanding 3D selection in virtual environments. Firstly, "Adaptive Selection Tasks" focus on targets whose characteristics change, reflecting the need for adaptability in real-world scenarios. The "Height Parameter" category emphasizes the importance of varying object heights in interaction design, using the base level as a reference to measure the height of the object. We also introduce the "Accessibility of Objects" category, which considers the necessity of manipulating objects to select targets, highlighting the interactive nature of 3D environments and it's impact on user mental models. We explore the use of "VR/AR games" as effective platforms for evaluating 3D selection techniques, due to their immersive challenges and opportunities, as well as the goal of winning. Lastly, "Immersive Data Visualization" is discussed as a task parameter, where the complexity and structure of visualized data significantly influence interaction design. These categories collectively aim to enhance our understanding and assessment of 3D selection techniques in various contexts.

Our review of the literature has also revealed a common methodology used by most researchers to evaluate the proposed 3D selection techniques. This method consists of a two-phase approach involving user studies. In the first phase, researchers conduct an initial user study designed to evaluate a selection technique in simple virtual scenes and analyze user performance and user experience. Then, researchers move on to a second study aimed at testing how adaptable and versatile this technique is in different and more complex task environments. This allows researchers to highlight their contribution, as well as reveal the advantages and disadvantages of the proposed techniques.

We also wanted to ensure that we included all research papers related to 3D object selection. After carefully investigating the terms "3D," "selection," and "3D selection," we did not find any clear differences between them. We found that "selection" and "3D selection" appeared to be used interchangeably or without significant differentiation in the literature. The absence of clear differences shows the need for precise terminology and clear definitions within the field to ensure a consistent understanding among researchers and practitioners.

6.1 Limitations

In this paper, we examine the evaluation factors for 3D virtual task environments related to the 3D selection methods only and, thus, the types of problems they were trying to solve. Therefore, we also discussed the evaluation criteria described in the literature. Topics such as the classification of interaction techniques, modalities, hardware, and software, assessment criteria, detailed observations, and insights on previous studies were not the focus of this paper.

Workshop papers and posters are typically considered as non-archival publications, allowing for future expansion and potential publication in other conferences or journals. For this reason, we have excluded workshop papers from our database.

It is important to note that our analysis exclusively focused on papers written in the English language. This deliberate choice of language criteria allowed us to maintain consistency and facilitate a more in-depth examination of the selected papers within our research scope.

7 Conclusion

In this paper, we examined virtual task environment parameters used in 3D selection studies. Our primary objective was to classify the virtual environments utilized for evaluating interaction methods in accordance with the parameters established by LaViola et al. [115]. Going beyond this foundation, we also contribute to the existing literature by proposing novel task environment parameters tailored to the design of virtual environments.

In the context of 3D selection methods, we emphasize that there is no *de facto* virtual task environments factor that can be used to evaluate 3D selection techniques. The collection of various studies presented in this paper highlights the importance of continuously exploring new task environment parameters and evaluation methodologies when designing and assessing virtual task environments. Such studies will be crucial to obtaining a comprehensive understanding of both the potential and limitations associated with newly developed 3D selection methods and interaction techniques, thus advancing the state-of-the-art in VR research.

We hope that the insights derived from our research will serve as a valuable resource for researchers, developers, designers, and practitioners engaged in the selection and customization of task environment parameters for the evaluation of their respective 3D interaction techniques.

References

[1] M. Achibet, A. Girard, M. Marchal, and A. Lécuyer. Leveraging passive haptic feedback in virtual environments with the elastic-arm approach. *Presence*, 25(1):17–32, 2016.

[2] M. Achibet, A. Girard, A. Talvas, M. Marchal, and A. Lécuyer. Elastic-arm: Human-scale passive haptic feedback for augmenting interaction and perception in virtual environments. In *2015 IEEE Virtual Reality (VR)*, pp. 63–68, 2015. doi: 10.1109/VR.2015.7223325

[3] R. Ajaj, C. Jacquemin, and F. Vernier. Rvdt: A design space for multiple input devices, multipleviews and multiple display surfaces combination. In *Proceedings of the 2009 International Conference on Multimodal Interfaces*, ICMI-MLMI '09, p. 269–276. Association for Computing Machinery, New York, NY, USA, 2009. doi: 10.1145/1647314.1647372

[4] M. Alex, D. Lottridge, J. Lee, S. Marks, and B. Wüensche. Discrete versus continuous colour pickers impact colour selection in virtual reality art-making. In *Proceedings of the 32nd Australian Conference on Human-Computer Interaction*, OzCHI '20, p. 158–169. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3441000.3441054

[5] C. Antonya. Accuracy of gaze point estimation in immersive 3d interaction interface based on eye tracking. pp. 1125–1129, 2012. doi: 10.1109/ICARCV.2012.6485315

[6] F. Argelaguet and C. Andujar. Efficient 3d pointing selection in cluttered virtual environments. *IEEE Computer Graphics and Applications*, 29(6):34–43, 2009. doi: 10.1109/MCG.2009.117

[7] F. Argelaguet and C. Andujar. Efficient 3d pointing selection in cluttered virtual environments. *IEEE Computer Graphics and Applications*, 29(6):34–43, 2009.

[8] F. Argelaguet and C. Andujar. Visual feedback techniques for virtual pointing on stereoscopic displays. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, pp. 163–170, 2009.

[9] F. Argelaguet and C. Andujar. A survey of 3d object selection techniques for virtual environments. *Computers & Graphics*, 37(3):121–136, 2013.

[10] F. Argelaguet, C. Andujar, and R. Trueba. Overcoming eye-hand visibility mismatch in 3d pointing selection. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology*, VRST '08, p. 43–46. Association for Computing Machinery, New York, NY, USA, 2008. doi: 10.1145/1450579.1450588

[11] F. Argelaguet, C. Andujar, and R. Trueba. Overcoming eye-hand visibility mismatch in 3d pointing selection. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, pp. 43–46, 2008.

[12] O. Ariza, G. Bruder, N. Katzakis, and F. Steinicke. Analysis of proximity-based multimodal feedback for 3d selection in immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 327–334, 2018. doi: 10.1109/VR.2018.8446317

[13] O. Ariza, G. Bruder, N. Katzakis, and F. Steinicke. Analysis of proximity-based multimodal feedback for 3d selection in immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 327–334. IEEE, 2018.

[14] O. J. Ariza N., M. Lange, F. Steinicke, and G. Bruder. Vibrotactile assistance for user guidance towards selection targets in vr and the cognitive resources involved. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 95–98, 2017. doi: 10.1109/3DUI.2017.7893323

[15] R. Arora, R. Habib Kazi, T. Grossman, G. Fitzmaurice, and K. Singh. Symbiosissketch: Combining 2d & 3d sketching for designing detailed 3d objects in situ. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, p. 1–15. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3173574.3173759

[16] K. Asai, T. Kondo, H. Kobayashi, and A. Mizuki. A geographic surface browsing tool using map-based augmented reality. In *2008 International Conference Visualisation*, pp. 93–98, 2008. doi: 10.1109/VIS.2008.25

[17] V. Asokan, S. Bateman, and A. Tang. Assistance for target selection in mobile augmented reality. In *Graphics Interface 2020*, 2020.

[18] S. Babu, M.-H. Tsai, T.-W. Hsu, and J.-H. Chuang. An evaluation of the efficiency of popular personal space pointing versus controller based spatial selection in vr. In *ACM Symposium on Applied Perception 2020*, SAP '20. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3385955.3407939

[19] S. Babu, M.-H. Tsai, T.-W. Hsu, and J.-H. Chuang. An evaluation of the efficiency of popular personal space pointing versus controller based spatial selection in vr. In *ACM Symposium on Applied Perception 2020*, pp. 1–10, 2020.

[20] M. Bachynskyi, V. Paneva, and J. Müller. Levicursor: Dexterous interaction with a levitating object. In *Proceedings of the 2018 ACM International Conference on Interactive Surfaces and Spaces*, ISS '18, p. 253–262. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3279778.3279802

[21] F. Bacim, R. Kopper, and D. A. Bowman. Design and evaluation of 3d selection techniques based on progressive refinement. *International Journal of Human-Computer Studies*, 71(7-8):785–802, 2013.

[22] C. Bailly, F. Leitner, and L. Nigay. Head-controlled menu in mixed reality with a hmd. In *Human-Computer Interaction–INTERACT 2019: 17th IFIP TC 13 International Conference, Paphos, Cyprus, September 2–6, 2019, Proceedings, Part IV 17*, pp. 395–415. Springer, 2019.

[23] B. Bajer, R. J. Teather, and W. Sturzlinger. Effects of stereo and head tracking in 3d selection tasks. In *Proceedings of the 1st symposium on Spatial user interaction*, pp. 77–77, 2013.

[24] M. Baloup, T. Pietrzak, and G. Casiez. Raycursor: A 3d pointing facilitation technique based on raycasting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2019.

[25] M. Baloup, T. Pietrzak, and G. Casiez. Raycursor: A 3d pointing facilitation technique based on raycasting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19,

p. 1–12. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300331
[26] M. D. Barrera Machuca and W. Stuerzlinger. The effect of stereo display deficiencies on virtual hand pointing. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–14. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300437
[27] M. D. Barrera Machuca and W. Stuerzlinger. The effect of stereo display deficiencies on virtual hand pointing. In *Proceedings of the 2019 CHI conference on human factors in computing systems*, pp. 1–14, 2019.
[28] A. U. Batmaz, M. D. Barrera Machuca, J. Sun, and W. Stuerzlinger. The effect of the vergence-accommodation conflict on virtual hand pointing in immersive displays. In *CHI Conference on Human Factors in Computing Systems*, pp. 1–15, 2022.
[29] A. U. Batmaz, M. Hudhud Mughrabi, M. D. Barrera Machuca, and W. Stuerzlinger. Effect of stereo deficiencies on virtual distal pointing. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*, VRST '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3562939.3565621
[30] A. U. Batmaz, M. D. B. Machuca, D. M. Pham, and W. Stuerzlinger. Do head-mounted display stereo deficiencies affect 3d pointing tasks in ar and vr? In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 585–592. IEEE, 2019.
[31] A. U. Batmaz, A. K. Mutasim, and W. Stuerzlinger. Precision vs. power grip: A comparison of pen grip styles for selection in virtual reality. In *2020 IEEE conference on virtual reality and 3D user interfaces abstracts and workshops (VRW)*, pp. 23–28. IEEE, 2020.
[32] A. U. Batmaz and W. Stuerzlinger. Effects of 3d rotational jitter and selection methods on 3d pointing tasks. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1687–1692. IEEE, 2019.
[33] A. U. Batmaz, K. Yu, H.-N. Liang, and W. Stuerzlinger. Improving effective throughput performance using auditory feedback in virtual reality. In *Symposium on Spatial User Interaction*, pp. 1–11, 2022.
[34] A. Bellarbi, N. Zenati, S. Otmane, H. Belghit, S. Benbelkacem, A. Messaci, and M. Hamidia. A 3d interaction technique for selection and manipulation distant objects in augmented reality. In *2017 5th International Conference on Electrical Engineering - Boumerdes (ICEE-B)*, pp. 1–5, 2017. doi: 10.1109/ICEE-B.2017.8192012
[35] B. Benda, S. Esmaeili, and E. D. Ragan. Determining detection thresholds for fixed positional offsets for virtual hand remapping in virtual reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 269–278. IEEE, 2020.
[36] H. Benko and S. Feiner. Balloon selection: A multi-finger technique for accurate low-fatigue 3d selection. In *2007 IEEE Symposium on 3D User Interfaces*, 2007. doi: 10.1109/3DUI.2007.340778
[37] H. Benko and S. Feiner. Balloon selection: A multi-finger technique for accurate low-fatigue 3d selection. In *2007 IEEE symposium on 3D user interfaces*. IEEE, 2007.
[38] S. Bhowmick. Exploring body gestures for small object selection in dense environment in hmd vr for data visualization applications. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 713–714, 2021. doi: 10.1109/VRW52623.2021.00239
[39] S. Bhowmick, P. Kalita, and K. Sorathia. A gesture elicitation study for selection of nail size objects in a dense and occluded dense hmd-vr. In *Proceedings of the 11th Indian Conference on Human-Computer Interaction*, pp. 12–23, 2020.
[40] D. A. Bowman, D. B. Johnson, and L. F. Hodges. Testbed evaluation of virtual environment interaction techniques. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 26–33, 1999.
[41] D. Brickler, R. J. Teather, A. T. Duchowski, and S. V. Babu. A fitts' law evaluation of visuo-haptic fidelity and sensory mismatch on user performance in a near-field disc transfer task in virtual reality. *ACM Trans. Appl. Percept.*, 17(4), dec 2020. doi: 10.1145/3419986
[42] G. Bruder, F. Steinicke, and W. Stürzlinger. Effects of visual conflicts on 3d selection task performance in stereoscopic display environments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 115–118. IEEE, 2013.
[43] G. Bruder, F. Steinicke, and W. Sturzlinger. To touch or not to touch? comparing 2d touch and 3d mid-air interaction on stereoscopic tabletop surfaces. In *Proceedings of the 1st symposium on Spatial user interaction*, pp. 9–16, 2013.
[44] G. Bruder, F. Steinicke, and W. Stürzlinger. Effects of visual conflicts on 3d selection task performance in stereoscopic display environments. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 115–118, 2013. doi: 10.1109/3DUI.2013.6550207
[45] M. Bustamante, M. Livingston, J. Hilley, H. Tran, E. Lovejoy, and J. T. Murray. Colorbound: Comparing menu dynamics in virtual reality. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 914–915, 2022. doi: 10.1109/VRW55335.2022.00308
[46] T. Butkiewicz, A. H. Stevens, and C. Ware. Multi-touch 3d positioning with the pantograph technique. In *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*, I3D '19. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3306131.3317014
[47] R. Canales and S. Jörg. Performance is not everything: Audio feedback preferred over visual feedback for grasping task in virtual reality. In *Proceedings of the 13th ACM SIGGRAPH Conference on Motion, Interaction and Games*, MIG '20. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3424636.3426897
[48] R. Canales and S. Jörg. Performance is not everything: Audio feedback preferred over visual feedback for grasping task in virtual reality. In *Proceedings of the 13th ACM SIGGRAPH Conference on Motion, Interaction and Games*, pp. 1–6, 2020.
[49] J. Cashion, C. Wingrave, and J. J. LaViola. Optimal 3d selection technique assignment using real-time contextual analysis. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 107–110, 2013. doi: 10.1109/3DUI.2013.6550205
[50] J. Cashion, C. Wingrave, and J. J. LaViola. Optimal 3d selection technique assignment using real-time contextual analysis. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 107–110. IEEE, 2013.
[51] J. Cashion, C. Wingrave, and J. J. LaViola Jr. Dense and dynamic 3d selection for game-based virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):634–642, 2012. doi: 10.1109/TVCG.2012.40
[52] J. Cashion, C. Wingrave, and J. J. LaViola Jr. Dense and dynamic 3d selection for game-based virtual environments. *IEEE transactions on visualization and computer graphics*, 18(4):634–642, 2012.
[53] J. A. Cashion, C. Wingrave, and J. J. LaViola. Automatic 3d selection technique assignment using real-time scenario analysis. In *2013 IEEE Virtual Reality (VR)*, pp. 103–104, 2013. doi: 10.1109/VR.2013.6549383
[54] J. A. Cashion, C. Wingrave, and J. J. LaViola. Automatic 3d selection technique assignment using real-time scenario analysis. In *2013 IEEE Virtual Reality (VR)*, pp. 103–104. IEEE, 2013.
[55] L. Chan, Y.-C. Liao, G. B. Mo, J. J. Dudley, C.-L. Cheng, P. O. Kristensson, and A. Oulasvirta. Investigating positive and negative qualities of human-in-the-loop optimization for designing interaction techniques. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3491102.3501850
[56] C.-H. Chen and J.-L. Wang. The semantic meaning of hand shapes and z-dimension movements of freehand distal pointing on large displays. *Symmetry*, 12(3):329, 2020.
[57] Y. Chen, J. Sun, Q. Xu, E. Lank, P. Irani, and W. Li. Global scene filtering, exploration, and pointing in occluded virtual space. In *IFIP Conference on Human-Computer Interaction*, pp. 156–176. Springer, 2021.
[58] A. Choumane, G. Casiez, and L. Grisoni. Buttonless clicking: Intuitive select and pick-release through gesture analysis. In *2010 IEEE Virtual Reality Conference (VR)*, pp. 67–70, 2010. doi: 10.1109/VR.2010.5444810
[59] D. Clergeaud and P. Guitton. Pano: Design and evaluation of a 360° through-the-lens technique. In *2017 IEEE Symposium on 3D User*

Interfaces (3DUI), pp. 2–11, 2017. doi: 10.1109/3DUI.2017.7893311

[60] R. M. Clifford, N. M. B. Tuanquin, and R. W. Lindeman. Jedi force-extension: Telekinesis as a virtual reality interaction metaphor. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 239–240, 2017. doi: 10.1109/3DUI.2017.7893360

[61] M. Cordeil, B. Bach, A. Cunningham, B. Montoya, R. T. Smith, B. H. Thomas, and T. Dwyer. Embodied axes: Tangible, actuated interaction for 3d augmented reality data spaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–12. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376613

[62] N.-T. Dang. A survey and classification of 3d pointing techniques. In *2007 IEEE international conference on research, innovation and vision for the future*, pp. 71–80. IEEE, 2007.

[63] N.-T. Dang, V. Perrot, and D. Mestre. Effects of sensory feedback while interacting with graphical menus in virtual environments. In *2011 IEEE Virtual Reality Conference*, pp. 199–200, 2011. doi: 10.1109/VR.2011.5759467

[64] R. Darbar, J. Odicio-Vilchez, T. Lainé, A. Prouzeau, and M. Hachet. Text selection in ar-hmd using a smartphone as an input device. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 526–527, 2021. doi: 10.1109/VRW52623.2021.00145

[65] R. Darbar, A. Prouzeau, and M. Hachet. Holocmds: Investigating around field of view glanceable commands selection in ar-hmds. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 876–877, 2022. doi: 10.1109/VRW55335.2022.00289

[66] M. M. Davis, J. L. Gabbard, D. A. Bowman, and D. Gracanin. Depth-based 3d gesture multi-level radial menu for virtual object manipulation. In *2016 IEEE Virtual Reality (VR)*, pp. 169–170, 2016. doi: 10.1109/VR.2016.7504707

[67] W. Delamare, M. Daniel, and K. Hasan. Multifingerbubble: A 3d bubble cursor variation for dense environments. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts*, pp. 1–6, 2022.

[68] S. Deng, J. Chang, S.-M. Hu, and J. J. Zhang. Gaze modulated disambiguation technique for gesture control in 3d virtual objects selection. In *2017 3rd IEEE International Conference on Cybernetics (CYBCONF)*, pp. 1–8, 2017. doi: 10.1109/CYBConf.2017.7985779

[69] S. Deng, J. Chang, S.-M. Hu, and J. J. Zhang. Gaze modulated disambiguation technique for gesture control in 3d virtual objects selection. In *2017 3rd IEEE International Conference on Cybernetics (CYBCONF)*, pp. 1–8. IEEE, 2017.

[70] T. J. Dube, Y. Ren, H. Limerick, I. S. MacKenzie, and A. S. Arif. Push, tap, dwell, and pinch: Evaluation of four mid-air selection methods augmented with ultrasonic haptic feedback. *Proc. ACM Hum.-Comput. Interact.*, 6(ISS), nov 2022. doi: 10.1145/3567718

[71] A. Dunk, A. Haffegee, and V. Alexandrov. Selection methods for interactive creation and management of objects in 3d immersive environments. *Procedia Computer Science*, 1(1):2609–2617, 2010.

[72] E. Ebrahimi, S. V. Babu, C. C. Pagano, and S. Jörg. An empirical evaluation of visuo-haptic feedback on physical reaching behaviors during 3d interaction in real and immersive virtual environments. *ACM Trans. Appl. Percept.*, 13(4), jul 2016. doi: 10.1145/2947617

[73] S. Eroglu, F. Stefan, A. Chevalier, D. Roettger, D. Zielasko, T. W. Kuhlen, and B. Weyers. Design and evaluation of a free-hand vr-based authoring environment for automated vehicle testing. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 1–10, 2021. doi: 10.1109/VR50410.2021.00020

[74] A. Esteves, D. Verweij, L. Suraiya, R. Islam, Y. Lee, and I. Oakley. Smoothmoves: Smooth pursuits head movements for augmented reality. In *Proceedings of the 30th annual acm symposium on user interface software and technology*, pp. 167–178, 2017.

[75] P. M. Fitts. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of experimental psychology*, 47(6):381, 1954.

[76] G. Fouché, F. Argelaguet Sanz, E. Faure, and C. Kervrann. Timeline design space for immersive exploration of time-varying spatial 3d data. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*, VRST '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3562939.3565612

[77] P. Ganapathi and K. Sorathia. Investigating controller less input methods for smartphone based virtual reality platforms. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, pp. 166–173, 2018.

[78] S. Garbaya and V. Hugel. Modelling movement time for haptic-enabled virtual assembly. In *VISIGRAPP 2020: 15th International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications*, 2020.

[79] P. Gonçalves, J. Orlosky, and T.-K. Machulla. An augmented reality assistant to support button selection for patients with age-related macular degeneration. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 730–731, 2020. doi: 10.1109/VRW50115.2020.00216

[80] J. G. Grandi, H. G. Debarba, L. Nedel, and A. Maciel. Design and evaluation of a handheld-based 3d user interface for collaborative object manipulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, p. 5881–5891. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3025453.3025935

[81] T. Grossman and R. Balakrishnan. The design and evaluation of selection techniques for 3d volumetric displays. In *Proceedings of the 19th annual ACM symposium on User interface software and technology*, pp. 3–12, 2006.

[82] T. Ha, M. Billinghurst, and W. Woo. An interactive 3d movement path manipulation method in an augmented reality environment. *Interacting with Computers*, 24(1):10–24, 2012. doi: 10.1016/j.intcom.2011.06.006

[83] N. A. B. A. Halim and A. W. B. Ismail. Arhome: Object selection and manipulation using raycasting technique with 3d-model tracking in handheld augmented reality. In *2021 IEEE 6th International Conference on Computing, Communication and Automation (ICCCA)*, pp. 254–259, 2021. doi: 10.1109/ICCCA52192.2021.9666416

[84] D. Han, D. Kim, and I. Cho. Portal: Portal widget for remote target acquisition and control in immersive virtual environments. In *Proceedings of the 28th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–11, 2022.

[85] D. T. Han, M. Suhail, and E. D. Ragan. Evaluating remapped physical reach for hand interactions with passive haptics in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 24(4):1467–1476, 2018. doi: 10.1109/TVCG.2018.2794659

[86] C. Hand. A survey of 3d interaction techniques. In *Computer graphics forum*, vol. 16, pp. 269–281. Wiley Online Library, 1997.

[87] J. Hartmann and D. Vogel. An examination of mobile phone pointing in surface mapped spatial augmented reality. *International Journal of Human-Computer Studies*, 153:102662, 2021.

[88] R. Henrikson, T. Grossman, S. Trowbridge, D. Wigdor, and H. Benko. Head-coupled kinematic template matching: A prediction model for ray pointing in vr. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2020.

[89] A. Hill and A. Johnson. Withindows: A framework for transitional desktop and immersive user interfaces. In *2008 IEEE Symposium on 3D User Interfaces*, pp. 3–10, 2008. doi: 10.1109/3DUI.2008.4476584

[90] J. D. Hincapié-Ramos, K. Ozacar, P. P. Irani, and Y. Kitamura. Gyrowand: Imu-based raycasting for augmented reality head-mounted displays. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, SUI '15, p. 89–98. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2788940.2788947

[91] F. Homps, Y. Beugin, and R. Vuillemot. Revivd: Exploration and filtering of trajectories in an immersive environment using 3d shapes. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 729–737. IEEE, 2020.

[92] J. Hong, F. A. Sanz, A. Trubuil, and T. Isenberg. Design and evaluation of three selection techniques for tightly packed 3d objects in cell lineage specification in botany. In *GI 2021-Graphics Interface*, pp. 213–223, 2021.

[93] A. Hopp, D. Schulz, W. Burgard, A. Cremers, and D. Fellner. Virtual reality visualization of distributed tele-experiments. In *IECON '98.*

Proceedings of the 24th Annual Conference of the IEEE Industrial Electronics Society (Cat. No.98CH36200), vol. 4, pp. 2210–2215 vol.4, 1998. doi: 10.1109/IECON.1998.724064

[94] B. J. Hou, J. P. Hansen, C. Uyanik, P. Bækgaard, S. Puthusserypady, J. M. Araujo, and S. MacKenzie. Feasibility of a device for gaze interaction by visually-evoked brain signals. In *2022 Symposium on Eye Tracking Research and Applications*, ETRA '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3517031.3529232

[95] S. Hubenschmid, J. Zagermann, S. Butscher, and H. Reiterer. Stream: Exploring the combination of spatially-aware tablets with augmented reality head-mounted displays for immersive analytics. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2021.

[96] ISO 9241-411:2012. Ergonomics of human-system interaction – part 411: Evaluation methods for the design of physical input devices. ISO, May 2012.

[97] B. Jackson, B. Jelke, and G. Brown. Yea big, yea high: A 3d user interface for surface selection by progressive refinement in virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 320–326. IEEE, 2018.

[98] Y. Jang, I. Jeon, T.-K. Kim, and W. Woo. Metaphoric hand gestures for orientation-aware vr object manipulation with an egocentric viewpoint. *IEEE Transactions on Human-Machine Systems*, 47(1):113–127, 2017. doi: 10.1109/THMS.2016.2611824

[99] Y. Jang, S.-T. Noh, H. J. Chang, T.-K. Kim, and W. Woo. 3d finger cape: Clicking action and position estimation under self-occlusions in egocentric viewpoint. *IEEE Transactions on Visualization and Computer Graphics*, 21(4):501–510, 2015. doi: 10.1109/TVCG.2015.2391860

[100] Y. Jang, S.-T. Noh, H. J. Chang, T.-K. Kim, and W. Woo. 3d finger cape: Clicking action and position estimation under self-occlusions in egocentric viewpoint. *IEEE Transactions on Visualization and Computer Graphics*, 21(4):501–510, 2015.

[101] I. Janzen, V. K. Rajendran, and K. S. Booth. Modeling the impact of depth on pointing performance. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pp. 188–199, 2016.

[102] H. Jiang, D. Weng, X. Dongye, and Y. Liu. A pinch-based text entry method for head-mounted displays. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 646–647, 2022. doi: 10.1109/VRW55335.2022.00174

[103] M. Kapinus, D. Bambušek, Z. Materna, V. Beran, and P. Smrž. Improved indirect virtual objects selection methods for cluttered augmented reality environments on mobile devices. In *2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pp. 834–838. IEEE, 2022.

[104] M. Kapinus, D. Bambušek, Z. Materna, V. Beran, and P. Smrž. Improved indirect virtual objects selection methods for cluttered augmented reality environments on mobile devices. In *Proceedings of the 2022 ACM/IEEE International Conference on Human-Robot Interaction*, HRI '22, p. 834–838. IEEE Press, 2022.

[105] M. Kenoui and M. A. Mehdi. Teach-me dna: an interactive course using voice output in an augmented reality system. In *2020 1st International Conference on Communications, Control Systems and Signal Processing (CCSSP)*, pp. 260–265. IEEE, 2020.

[106] W. Kim and S. Xiong. Viewfindervr: configurable viewfinder for selection of distant objects in vr. *Virtual Reality*, 26(4):1573–1592, 2022.

[107] R. Kopper, F. Bacim, and D. A. Bowman. Rapid and accurate 3d selection by progressive refinement. In *2011 IEEE symposium on 3D user interfaces (3DUI)*, pp. 67–74. IEEE, 2011.

[108] P. Kourtesis, S. Vizcay, M. Marchal, C. Pacchierotti, and F. Argelaguet. Action-specific perception & performance on a fitts's law task in virtual reality: The role of haptic feedback. *IEEE Transactions on Visualization and Computer Graphics*, 28(11):3715–3726, 2022.

[109] M. Krichenbauer, G. Yamamoto, T. Taketom, C. Sandor, and H. Kato. Augmented reality versus virtual reality for 3d object manipulation. *IEEE Transactions on Visualization and Computer Graphics*, 24(2):1038–1048, 2018. doi: 10.1109/TVCG.2017.2658570

[110] M. Krichenbauer, G. Yamamoto, T. Taketomi, C. Sandor, H. Kato, and S. Feiner. Evaluating the effect of positional head-tracking on task performance in 3d modeling user interfaces. *Computers & Graphics*, 65:22–30, 2017.

[111] A. Kulshreshth, J. Schild, and J. J. LaViola. Evaluating user performance in 3d stereo and motion enabled video games. In *Proceedings of the International Conference on the Foundations of Digital Games*, FDG '12, p. 33–40. Association for Computing Machinery, New York, NY, USA, 2012. doi: 10.1145/2282338.2282350

[112] A. Kunert, A. Kulik, C. Lux, and B. Fröhlich. Facilitating system control in ray-based interaction tasks. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, VRST '09, p. 183–186. Association for Computing Machinery, New York, NY, USA, 2009. doi: 10.1145/1643928.1643969

[113] S. Kyian and R. Teather. Selection performance using a smartphone in vr with redirected input. In *Proceedings of the 2021 ACM Symposium on Spatial User Interaction*, SUI '21. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3485279.3485292

[114] J. Lacoche, T. Duval, B. Arnaldi, E. Maisel, and J. Royan. Machine learning based interaction technique selection for 3d user interfaces. In *Virtual Reality and Augmented Reality: 16th EuroVR International Conference, EuroVR 2019, Tallinn, Estonia, October 23–25, 2019, Proceedings 16*, pp. 33–51. Springer, 2019.

[115] J. J. LaViola Jr, E. Kruijff, R. P. McMahan, D. Bowman, and I. P. Poupyrev. *3D user interfaces: theory and practice*. Addison-Wesley Professional, 2017.

[116] K.-D. Le, T. Q. Tran, K. Chlasta, K. Krejtz, M. Fjeld, and A. Kunz. Vxslate: Exploring combination of head movements and mobile touch for large virtual display interaction. In *Designing Interactive Systems Conference 2021*, DIS '21, p. 283–297. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3461778.3462076

[117] H. Lee, S.-T. Noh, and W. Woo. Tunnelslice: Freehand subspace acquisition using an egocentric tunnel for wearable augmented reality. *IEEE Transactions on Human-Machine Systems*, 47(1):128–139, 2017. doi: 10.1109/THMS.2016.2611821

[118] J.-J. Lee and J.-M. Park. 3d mirrored object selection for occluded objects in virtual environments. *IEEE Access*, 8:200259–200274, 2020. doi: 10.1109/ACCESS.2020.3035376

[119] J.-J. Lee and J.-M. Park. 3d mirrored object selection for occluded objects in virtual environments. *IEEE Access*, 8:200259–200274, 2020.

[120] J. Leng, L. Wang, X. Liu, X. Shi, and M. Wang. Efficient flower text entry in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 28(11):3662–3672, 2022. doi: 10.1109/TVCG.2022.3203101

[121] H. Li and L. Fan. A flexible technique to select objects via convolutional neural network in vr space. *Science China Information Sciences*, 63:1–20, 2020.

[122] J. Li, I. Cho, and Z. Wartell. Evaluation of cursor offset on 3d selection in vr. In *Proceedings of the 2018 ACM Symposium on Spatial User Interaction*, SUI '18, p. 120–129. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3267782.3267797

[123] N. Li, T. Han, F. Tian, J. Huang, M. Sun, P. Irani, and J. Alexander. Get a grip: Evaluating grip gestures for vr input using a lightweight pen. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376698

[124] Z. H. Lim and P. O. Kristensson. An evaluation of discrete and continuous mid-air loop and marking menu selection in optical see-through hmds. In *Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services*, pp. 1–10, 2019.

[125] C. J. Lin, D. Caesaron, and B. H. Woldegiorgis. The accuracy of the frontal extent in stereoscopic environments: A comparison of direct selection and virtual cursor techniques. *Plos one*, 14(9):e0222751, 2019.

[126] C. J. Lin, D. Caesaron, and B. H. Woldegiorgis. The effects of augmented reality interaction techniques on egocentric distance esti-

mation accuracy. *Applied Sciences*, 9(21):4652, 2019.

[127] N. G. Lipari and C. W. Borst. Handymenu: Integrating menu selection into a multifunction smartphone-based vr controller. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 129–132, 2015. doi: 10.1109/3DUI.2015.7131737

[128] L. Liu, J.-B. Martens, and R. Van Liere. Revisiting path steering for 3d manipulation tasks. *international Journal of Human-computer Studies*, 69(3):170–181, 2011.

[129] J. Looser, M. Billinghurst, R. Grasset, and A. Cockburn. An evaluation of virtual lenses for object selection in augmented reality. In *Proceedings of the 5th international conference on Computer graphics and interactive techniques in Australia and Southeast Asia*, pp. 203–210, 2007.

[130] X. Lou, Z. Chen, P. Hansen, and R. Peng. Asymmetric free-hand interaction on a large display and inspirations for designing natural user interfaces. *Symmetry*, 14(5):928, 2022.

[131] X. Lou, X. A. Li, P. Hansen, and P. Du. Hand-adaptive user interface: improved gestural interaction in virtual reality. *Virtual Reality*, 25:367–382, 2021.

[132] J.-B. Louvet and C. Fleury. Combining bimanual interaction and teleportation for 3d manipulation on multi-touch wall-sized displays. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, pp. 283–292, 2016.

[133] Y. Lu, C. Yu, and Y. Shi. Investigating bubble mechanism for ray-casting to improve 3d target acquisition in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 35–43, 2020. doi: 10.1109/VR46266.2020.00021

[134] Y. Lu, C. Yu, and Y. Shi. Investigating bubble mechanism for ray-casting to improve 3d target acquisition in virtual reality. In *2020 IEEE Conference on virtual reality and 3D user interfaces (VR)*, pp. 35–43. IEEE, 2020.

[135] P. Lubos, G. Bruder, O. Ariza, and F. Steinicke. Touching the sphere: Leveraging joint-centered kinespheres for spatial user interaction. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, SUI '16, p. 13–22. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2983310.2985753

[136] P. Lubos, G. Bruder, O. Ariza, and F. Steinicke. Touching the sphere: Leveraging joint-centered kinespheres for spatial user interaction. In *Proceedings of the 2016 symposium on spatial user interaction*, pp. 13–22, 2016.

[137] P. Lubos, G. Bruder, and F. Steinicke. Analysis of direct selection in head-mounted display environments. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 11–18, 2014. doi: 10.1109/3DUI.2014.6798834

[138] P. Lubos, G. Bruder, and F. Steinicke. Analysis of direct selection in head-mounted display environments. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 11–18. IEEE, 2014.

[139] S. Luo and R. J. Teather. Camera-based selection with cardboard hmds. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1066–1067, 2019. doi: 10.1109/VR.2019.8797772

[140] J. Ma, J. Qian, T. Zhou, and J. Huang. Focalpoint: Adaptive direct manipulation for selecting small 3d virtual objects. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 7(1):1–26, 2023.

[141] P. Maier, M. Tönnis, G. Klinker, A. Raith, M. Drees, and F. Kühn. What do you do when two hands are not enough? interactive selection of bonds between pairs of tangible molecules. In *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 83–90, 2010. doi: 10.1109/3DUI.2010.5444716

[142] M. Malekmakan, W. Stuerzlinger, and B. Riecke. Analyzing the trade-off between selection and navigation in vr. In *Proceedings of the 26th ACM Symposium on Virtual Reality Software and Technology*, pp. 1–3, 2020.

[143] D. Markov-Vetter, E. Moll, and O. Staadt. Evaluation of 3d selection tasks in parabolic flight conditions: Pointing task in augmented reality user interfaces. In *Proceedings of the 11th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry*, VRCAI '12, p. 287–294. Association for Computing Machinery, New York, NY, USA, 2012. doi: 10.1145/2407516.2407583

[144] D. Markov-Vetter, V. Zander, J. Latsch, and O. Staadt. Enhancement of direct augmented reality object selection by gravity-adapted target resizing. In *Computer Vision, Imaging and Computer Graphics Theory and Applications: 10th International Joint Conference, VISIGRAPP 2015, Berlin, Germany, March 11–14, 2015, Revised Selected Papers 10*, pp. 75–96. Springer, 2016.

[145] A. Marquardt, J. Maiero, E. Kruijff, C. Trepkowski, A. Schwandt, A. Hinkenjann, J. Schöning, and W. Stuerzlinger. Tactile hand motion and pose guidance for 3d interaction. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, VRST '18. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3281505.3281526

[146] A. Marquardt, C. Trepkowski, T. D. Eibich, J. Maiero, and E. Kruijff. Non-visual cues for view management in narrow field of view augmented reality displays. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 190–201. IEEE, 2019.

[147] A. Marquardt, C. Trepkowski, T. D. Eibich, J. Maiero, E. Kruijff, and J. Schöning. Comparing non-visual and visual guidance methods for narrow field of view augmented reality displays. *IEEE Transactions on Visualization and Computer Graphics*, 26(12):3389–3401, 2020.

[148] M. Maslych, Y. Hmaiti, R. Ghamandi, P. Leber, R. K. Kattoju, J. Belga, and J. J. LaViola. Toward intuitive acquisition of occluded vr objects through an interactive disocclusion mini-map. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pp. 460–470. IEEE, 2023.

[149] C. Mei, Y. Yang, and Y. Xu. Sightx: A 3d selection technique for xr. In *International Conference on Virtual Reality and Mixed Reality*, pp. 22–35. Springer, 2022.

[150] D. Mendes, F. M. Caputo, A. Giachetti, A. Ferreira, and J. Jorge. A survey on 3D virtual object manipulation: From the desktop to immersive virtual environments. In *Computer graphics forum*, vol. 38, pp. 21–45. Wiley Online Library, 2019.

[151] D. Mendes, D. Medeiros, E. Cordeiro, M. Sousa, A. Ferreira, and J. Jorge. Precious! out-of-reach selection using iterative refinement in vr. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 237–238, 2017. doi: 10.1109/3DUI.2017.7893359

[152] A. Messaci, N. Zenati, M. Belhocine, and S. Otmane. Zoom-fwd: Efficient technique for 3d gestual interaction with distant and occluded objects in virtual reality. *Computer Animation and Virtual Worlds*, 33(1):e2033, 2022.

[153] D. M. Mifsud, A. S. Williams, F. Ortega, and R. J. Teather. Augmented reality fitts' law input comparison between touchpad, pointing gesture, and raycast. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 590–591, 2022. doi: 10.1109/VRW55335.2022.00146

[154] P. Mohr, M. Tatzgern, T. Langlotz, A. Lang, D. Schmalstieg, and D. Kalkofen. Trackcap: Enabling smartphones for 3d interaction on mobile head-mounted displays. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, p. 1–11. Association for Computing Machinery, New York, NY, USA, 2019. doi: 10.1145/3290605.3300815

[155] R. A. Montano-Murillo, C. Nguyen, R. H. Kazi, S. Subramanian, S. DiVerdi, and D. Martinez-Plasencia. Slicing-volume: Hybrid 3d/2d multi-target selection technique for dense virtual environments. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 53–62, 2020. doi: 10.1109/VR46266.2020.00023

[156] R. A. Montano-Murillo, C. Nguyen, R. H. Kazi, S. Subramanian, S. DiVerdi, and D. Martinez-Plasencia. Slicing-volume: Hybrid 3d/2d multi-target selection technique for dense virtual environments. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 53–62. IEEE, 2020.

[157] R. A. Montano Murillo, S. Subramanian, and D. Martinez Plasencia. Erg-o: Ergonomic optimization of immersive virtual environments. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, UIST '17, p. 759–771. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3126594.3126605

[158] A. Moore, M. Kodeih, A. Singhania, A. Wu, T. Bashir, and R. McMahan. The importance of intersection disambiguation for virtual hand techniques. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 310–317. IEEE, 2019.

[159] A. G. Moore, J. G. Hatch, S. Kuehl, and R. P. McMahan. Vote: A ray-casting study of vote-oriented technique enhancements. *International Journal of Human-Computer Studies*, 120:36–48, 2018.
[160] A. Mossel and C. Koessler. Large scale cut plane: An occlusion management technique for immersive dense 3d reconstructions. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, VRST '16, p. 201–210. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2993369.2993384
[161] A. Mossel and C. Koessler. Large scale cut plane: An occlusion management technique for immersive dense 3d reconstructions. In *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, pp. 201–210, 2016.
[162] A. Mossel, B. Venditti, and H. Kaufmann. Drillsample: Precise selection in dense handheld augmented reality environments. In *Proceedings of the Virtual Reality International Conference: Laval Virtual*, VRIC '13. Association for Computing Machinery, New York, NY, USA, 2013. doi: 10.1145/2466816.2466827
[163] J. W. Nam, K. McCullough, J. Tveite, M. M. Espinosa, C. H. Perry, B. T. Wilson, and D. F. Keefe. Worlds-in-wedges: Combining worlds-in-miniature and portals to support comparative immersive visualization of forestry data. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 747–755, 2019. doi: 10.1109/VR.2019.8797871
[164] A. Nguyen and A. Banic. 3dtouch: A wearable 3d input device for 3d applications. In *2015 IEEE Virtual Reality (VR)*, pp. 55–61, 2015. doi: 10.1109/VR.2015.7223324
[165] O. Oda and S. Feiner. 3d referencing techniques for physical objects in shared augmented reality. In *2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 207–215, 2012. doi: 10.1109/ISMAR.2012.6402558
[166] K. E. L. Palmerius and J. Lundberg. Interaction design for selection and manipulation on immersive touch table display systems for 3d geographic visualization. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1064–1065, 2019. doi: 10.1109/VR.2019.8798126
[167] V. M. Pawar and A. Steed. Evaluating the influence of haptic force-feedback on 3d selection tasks using natural egocentric gestures. In *2009 IEEE Virtual Reality Conference*, pp. 11–18, 2009. doi: 10.1109/VR.2009.4810992
[168] V. M. Pawar and A. Steed. Profiling the behaviour of 3d selection tasks on movement time when using natural haptic pointing gestures. In *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, VRST '09, p. 79–82. Association for Computing Machinery, New York, NY, USA, 2009. doi: 10.1145/1643928.1643947
[169] V. M. Pawar and A. Steed. Poster: The effect of target size and force feedback on 3d selection within a co-located visual-haptic immersive virtual environment. In *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 169–170, 2013. doi: 10.1109/3DUI.2013.6550232
[170] F. Periverzov and H. Ilieş. Ids: The intent driven selection method for natural user interfaces. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 121–128, 2015. doi: 10.1109/3DUI.2015.7131736
[171] M. Pfeiffer and W. Stuerzlinger. 3d virtual hand selection with ems and vibration feedback. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, pp. 1361–1366, 2015.
[172] K. Pfeuffer, Y. Abdrabou, A. Esteves, R. Rivu, Y. Abdelrahman, S. Meitner, A. Saadi, and F. Alt. Artention: A design space for gaze-adaptive user interfaces in augmented reality. *Computers & Graphics*, 95:1–12, 2021.
[173] F. Picon, M. Ammi, and P. Bourdot. Case study of haptic methods for selection on cad models. In *2008 IEEE Virtual Reality Conference*, pp. 209–212, 2008. doi: 10.1109/VR.2008.4480775
[174] K. Pietroszek, A. Kuzminykh, J. R. Wallace, and E. Lank. Smartcasting: A discount 3d interaction technique for public displays. In *Proceedings of the 26th Australian Computer-Human Interaction Conference on Designing Futures: The Future of Design*, OzCHI '14, p. 119–128. Association for Computing Machinery, New York, NY, USA, 2014. doi: 10.1145/2686612.2686629
[175] C. Plasson, D. Cunin, Y. Laurillau, and L. Nigay. Tabletop ar with hmd and tablet: a comparative study for 3d selection. In *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*, pp. 409–414, 2019.
[176] C. Plasson, D. Cunin, Y. Laurillau, and L. Nigay. 3d tabletop ar: A comparison of mid-air, touch and touch+ mid-air interaction. In *Proceedings of the International Conference on Advanced Visual Interfaces*, pp. 1–5, 2020.
[177] C. Plasson, D. Cunin, Y. Laurillau, and L. Nigay. A lens-based extension of raycasting for accurate selection in dense 3d environments. In *IFIP Conference on Human-Computer Interaction*, pp. 501–524. Springer, 2021.
[178] H. Pohl, K. Lilija, J. McIntosh, and K. Hornbæk. Poros: configurable proxies for distant interactions in vr. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2021.
[179] N. F. Polys. Information visualization in virtual environments, 2014.
[180] I. Poupyrev, S. Weghorst, M. Billinghurst, and T. Ichikawa. A framework and testbed for studying manipulation techniques for immersive vr. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 21–28, 1997.
[181] M. Pourmemar and C. Poullis. Visualizing and interacting with hierarchical menus in immersive augmented reality. In *Proceedings of the 17th International Conference on Virtual-Reality Continuum and its Applications in Industry*, pp. 1–9, 2019.
[182] M. Prachyabrued and C. W. Borst. Visual feedback for virtual grasping. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 19–26, 2014. doi: 10.1109/3DUI.2014.6798835
[183] M. Prachyabrued and C. W. Borst. Design and evaluation of visual interpenetration cues in virtual grasping. *IEEE Transactions on Visualization and Computer Graphics*, 22(6):1718–1731, 2016. doi: 10.1109/TVCG.2015.2456917
[184] M. Prachyabrued, D. L. Ducrest, and C. W. Borst. Handymap: a selection interface for cluttered vr environments using a tracked hand-held touch device. In *International Symposium on Visual Computing*, pp. 45–54. Springer, 2011.
[185] Y. Y. Qian and R. J. Teather. The eyes don't have it: An empirical comparison of head-based and eye-based selection in virtual reality. In *Proceedings of the 5th Symposium on Spatial User Interaction*, SUI '17, p. 91–98. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3131277.3132182
[186] M. Rajab, A. R. Chaudhry, and M. Cherian. The development of 3d visualization and its potential impact on interior design and its clients. In *2019 Sixth HCT Information Technology Trends (ITT)*, pp. 160–165, 2019. doi: 10.1109/ITT48889.2019.9075098
[187] G. Ren, X. Liu, and J. Liu. Design and evaluation of 3d selection in mobile vr environments. In *2019 8th International Conference on Innovation, Communication and Engineering (ICICE)*, pp. 17–20, 2019. doi: 10.1109/ICICE49024.2019.9117494
[188] G. Ren and E. O'Neill. 3d marking menu selection with freehand gestures. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 61–68. IEEE, 2012.
[189] G. Ren and E. O'Neill. 3d selection with freehand gesture. *Computers & Graphics*, 37(3):101–120, 2013.
[190] T. Rick, A. von Kapri, and T. Kuhlen. Gpu implementation of 3d object selection by conic volume techniques in virtual environments. In *2010 IEEE Virtual Reality Conference (VR)*, pp. 243–246, 2010. doi: 10.1109/VR.2010.5444783
[191] H. Ro, S. Chae, I. Kim, J. Byun, Y. Yang, Y. Park, and T. Han. A dynamic depth-variable ray-casting interface for object manipulation in ar environments. In *2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pp. 2873–2878. IEEE, 2017.
[192] D. A. W. Rosa and H. H. Nagel. Selection techniques for dense and occluded virtual 3d environments, supported by depth feedback: Double, bound and depth bubble cursors. In *2010 XXIX International Conference of the Chilean Computer Science Society*, pp. 218–225, 2010. doi: 10.1109/SCCC.2010.51
[193] K. Ryu, W. Hwang, J.-J. Lee, J.-S. Kim, and J.-M. Park. Distant 3d object grasping with gaze-supported selection. In *2015 12th International Conference on Ubiquitous Robots and Ambient Intelligence*

(URAI), pp. 541–544, 2015. doi: 10.1109/URAI.2015.7358825

[194] K. Ryu, J.-J. Lee, and J.-M. Park. Gg interaction: a gaze–grasp pose interaction for 3d virtual object selection. *Journal on Multimodal User Interfaces*, 13(4):383–393, 2019.

[195] J. Salyers, D. Cliburn, K. Canniff, and S. Barajas. Evaluation of information widgets for a virtual reality serious game. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1627–1632, 2019. doi: 10.1109/VR.2019.8798150

[196] E. Samimi and R. J. Teather. Impress: Improved multi-touch progressive refinement selection strategy. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 304–309, 2022. doi: 10.1109/VRW55335.2022.00069

[197] E. Samimi and R. J. Teather. Multi-touch smartphone-based progressive refinement vr selection. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 582–583, 2022. doi: 10.1109/VRW55335.2022.00142

[198] M. Sandoval, T. Morris, and M. J. Turner. Controlling 3d visualisations with multiple degrees of freedom. In *CGVC*, pp. 97–101, 2019.

[199] G. Schmidt, Y. Baillot, D. Brown, E. Tomlin, and J. Swan. Toward disambiguating multiple selections for frustum-based pointing. In *3D User Interfaces (3DUI'06)*, pp. 87–94, 2006. doi: 10.1109/VR.2006.133

[200] D. Schön, T. Kosch, F. Müller, M. Schmitz, S. Günther, L. Bommhardt, and M. Mühlhäuser. Tailor twist: Assessing rotational mid-air interactions for augmented reality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–14, 2023.

[201] Y. A. Sekhavat. Privacy preserving cloth try-on using mobile augmented reality. *IEEE Transactions on Multimedia*, 19(5):1041–1049, 2017. doi: 10.1109/TMM.2016.2639380

[202] M. Sereno, L. Besançon, and T. Isenberg. Point specification in collaborative visualization for 3d scalar fields using augmented reality. *Virtual Reality*, 26(4):1317–1334, 2022.

[203] Z. Serrar, N. Elmarzouqi, Z. Jarir, and J.-C. Lapayre. Evaluation of disambiguation mechanisms of object-based selection in virtual environment: Which performances and features to support" pick out"? In *Proceedings of the XV international conference on human computer interaction*, pp. 1–8, 2014.

[204] M. Shi, T. Hu, and J. Yu. Pointing cursor interaction in virtual reality from the perspective of distance perception. *Traitement du Signal*, 39(2), 2022.

[205] R. Shi, J. Zhang, Y. Yue, L. Yu, and H.-N. Liang. Exploration of bare-hand mid-air pointing selection techniques for dense virtual reality environments. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–7, 2023.

[206] M. Shirazawa, H. Ohki, K. Gyohten, and N. Sueda. An impressive data animating for positional movement of soccer players. In *2006 SICE-ICASE International Joint Conference*, pp. 4755–4760, 2006. doi: 10.1109/SICE.2006.314784

[207] L. Sidenmark, C. Clarke, X. Zhang, J. Phu, and H. Gellersen. Outline pursuits: Gaze-assisted selection of occluded objects in virtual reality. In *Proceedings of the 2020 chi conference on human factors in computing systems*, pp. 1–13, 2020.

[208] A. Simon. Usability of multiviewpoint images for spatial interaction in projection-based display systems. *IEEE Transactions on Visualization and Computer Graphics*, 13(1):26–33, 2006.

[209] A. K. Singh, H.-T. Chen, Y.-F. Cheng, J.-T. King, L.-W. Ko, K. Gramann, and C.-T. Lin. Visual appearance modulates prediction error in virtual reality. *IEEE Access*, 6:24617–24624, 2018. doi: 10.1109/ACCESS.2018.2832089

[210] A. K. Singh, H.-T. Chen, K. Gramann, and C.-T. Lin. Intraindividual completion time modulates the prediction error negativity in a virtual 3-d object selection task. *IEEE Transactions on Cognitive and Developmental Systems*, 12(2):354–360, 2020. doi: 10.1109/TCDS.2020.2991301

[211] J. Smiley, B. Lee, S. Tandon, M. Cordeil, L. Besançon, J. Knibbe, B. Jenny, and T. Dwyer. The made-axis: A modular actuated device to embody the axis of a data dimension. *Proc. ACM Hum.-Comput. Interact.*, 5(ISS), nov 2021. doi: 10.1145/3488546

[212] R. T. Smith, B. Avery, and B. H. Thomas. Lightweight hand and arm tracking for mobile augmented reality. In *2008 12th IEEE International Symposium on Wearable Computers*, pp. 105–106, 2008. doi: 10.1109/ISWC.2008.4911595

[213] C. G. Song, N. J. Kwak, and D. H. Jeong. Developing an efficient technique of selection and manipulation in immersive ve. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pp. 142–146, 2000.

[214] R. Stenholt and C. B. Madsen. Poster: Brush, lasso, or magic wand? picking the right tool for large-scale multiple object selection tasks. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 163–164, 2012. doi: 10.1109/3DUI.2012.6184212

[215] W. Stuerzlinger and R. J. Teather. Considerations for targets in 3d pointing experiments. In *Proceedings of HCI Korea*, HCIK '15, p. 162–168. Hanbit Media, Inc., Seoul, KOR, 2014.

[216] G. E. Su, M. S. Sunar, and A. W. Ismail. Device-based manipulation technique with separated control structures for 3d object translation and rotation in handheld mobile ar. *International Journal of Human-Computer Studies*, 141:102433, 2020.

[217] S. Subramanian and W. IJsselsteijn. Survey and classification of spatial object manipulation techniques. In *Proceedings of OZCHI 2000*, pp. 330–337, 2000.

[218] J. Sun and W. Stuerzlinger. Selecting invisible objects. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 697–698, 2018. doi: 10.1109/VR.2018.8446199

[219] J. Sun and W. Stuerzlinger. Selecting invisible objects. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 697–698. IEEE, 2018.

[220] J. Sun, W. Stuerzlinger, and B. E. Riecke. Comparing input methods and cursors for 3d positioning with head-mounted displays. In *Proceedings of the 15th ACM Symposium on Applied Perception*, SAP '18. Association for Computing Machinery, New York, NY, USA, 2018. doi: 10.1145/3225153.3225167

[221] M. Sun, M. Cao, L. Wang, and Q. Qian. Phonecursor: Improving 3d selection performance with mobile device in ar. *IEEE Access*, 8:70616–70626, 2020. doi: 10.1109/ACCESS.2020.2986037

[222] X. Tang, X. Hu, C.-W. Fu, and D. Cohen-Or. Grabar: Occlusion-aware grabbing virtual objects in ar. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, pp. 697–708, 2020.

[223] D. Tao, X. Diao, T. Wang, J. Guo, and X. Qu. Freehand interaction with large displays: Effects of body posture, interaction distance and target size on task performance, perceived usability and workload. *Applied Ergonomics*, 93:103370, 2021.

[224] R. J. Teather, D. Natapov, and M. Jenkin. Evaluating haptic feedback in virtual environments using iso 9241–9. In *2010 IEEE Virtual Reality Conference (VR)*, pp. 307–308, 2010. doi: 10.1109/VR.2010.5444753

[225] R. J. Teather and W. Stuerzlinger. Guidelines for 3d positioning techniques. In *Proceedings of the 2007 Conference on Future Play*, Future Play '07, p. 61–68. Association for Computing Machinery, New York, NY, USA, 2007. doi: 10.1145/1328202.1328214

[226] R. J. Teather and W. Stuerzlinger. Pointing at 3d target projections with one-eyed and stereo cursors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, p. 159–168. Association for Computing Machinery, New York, NY, USA, 2013. doi: 10.1145/2470654.2470677

[227] R. J. Teather and W. Stuerzlinger. Visual aids in 3d point selection experiments. In *Proceedings of the 2nd ACM Symposium on Spatial User Interaction*, SUI '14, p. 127–136. Association for Computing Machinery, New York, NY, USA, 2014. doi: 10.1145/2659766.2659770

[228] R. J. Teather and W. Stuerzlinger. Visual aids in 3d point selection experiments. In *Proceedings of the 2nd ACM symposium on Spatial user interaction*, pp. 127–136, 2014.

[229] R. J. Teather and W. Stuerzlinger. Factors affecting mouse-based 3d selection in desktop vr systems. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, pp. 10–19, 2015.

[230] R. J. Teather and W. Stuerzlinger. Factors affecting mouse-based 3d selection in desktop vr systems. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, SUI '15, p. 10–19. Associa-

tion for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2788940.2788946

[231] W. Tong, Z. Chen, M. Xia, L. Y.-H. Lo, L. Yuan, B. Bach, and H. Qu. Exploring interactions with printed data visualizations in augmented reality. *IEEE Transactions on Visualization and Computer Graphics*, 1912.

[232] T. Q. Tran, H. Shin, W. Stuerzlinger, and J. Han. Effects of virtual arm representations on interaction in virtual environments. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, pp. 1–9, 2017.

[233] T. Q. Tran, H. Shin, W. Stuerzlinger, and J. Han. Effects of virtual arm representations on interaction in virtual environments. In *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, VRST '17. Association for Computing Machinery, New York, NY, USA, 2017. doi: 10.1145/3139131.3139149

[234] W.-J. Tseng, S. Huron, E. Lecolinet, and J. Gugenheimer. Fingermapper: Enabling arm interaction in confined spaces for virtual reality through finger mappings. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pp. 1–4, 2021.

[235] A. Ulinski, C. Zanbaka, Z. Wartell, P. Goolkasian, and L. F. Hodges. Two handed selection techniques for volumetric data. In *2007 IEEE Symposium on 3D User Interfaces*. IEEE, 2007.

[236] S. Uzor and P. O. Kristensson. An exploration of freehand crossing selection in head-mounted augmented reality. *ACM Trans. Comput.-Hum. Interact.*, 28(5), aug 2021. doi: 10.1145/3462546

[237] D. Valkov, A. Giesler, and K. Hinrichs. Evaluation of depth perception for touch interaction with stereoscopic rendered objects. In *Proceedings of the 2012 ACM international conference on Interactive tabletops and surfaces*, pp. 21–30, 2012.

[238] L. Vanacken, T. Grossman, and K. Coninx. Exploring the effects of environment density and target visibility on object selection in 3d virtual environments. In *2007 IEEE Symposium on 3D User Interfaces*, 2007. doi: 10.1109/3DUI.2007.340783

[239] L. Vanacken, T. Grossman, and K. Coninx. Exploring the effects of environment density and target visibility on object selection in 3d virtual environments. In *2007 IEEE symposium on 3D user interfaces*. IEEE, 2007.

[240] L. Vanacken, T. Grossman, and K. Coninx. Multimodal selection techniques for dense and occluded 3d virtual environments. *International Journal of Human-Computer Studies*, 67(3):237–255, 2009.

[241] P. V. Vemavarapu and C. W. Borst. Indirect touch interaction with stereoscopic displays using a two-sided handheld touch device. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 209–210, 2017. doi: 10.1109/3DUI.2017.7893345

[242] V. Vuibert, W. Stuerzlinger, and J. R. Cooperstock. Evaluation of docking task performance using mid-air interaction techniques. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, SUI '15, p. 44–52. Association for Computing Machinery, New York, NY, USA, 2015. doi: 10.1145/2788940.2788950

[243] G. Wang, G. Ren, X. Hong, X. Peng, W. Li, and E. O'Neill. Freehand gestural selection with haptic feedback in wearable optical see-through augmented reality. *Information*, 13(12):566, 2022.

[244] L. Wang, J. Chen, Q. Ma, and V. Popescu. Disocclusion headlight for selection assistance in vr. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 216–225, 2021. doi: 10.1109/VR50410.2021.00043

[245] L. Wang, J. Chen, Q. Ma, and V. Popescu. Disocclusion headlight for selection assistance in vr. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 216–225. IEEE, 2021.

[246] M. Wang, Y. Hu, C. Li, and X. Shen. Magiccube: A one-handed interaction approach in 3d environment on smartphones. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 538–539, 2021. doi: 10.1109/VRW52623.2021.00151

[247] M. Wang, Z.-M. Ye, J.-C. Shi, and Y.-L. Yang. Scene-context-aware indoor object selection and movement in vr. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 235–244, 2021. doi: 10.1109/VR50410.2021.00045

[248] M. Wang, Z.-M. Ye, J.-C. Shi, and Y.-L. Yang. Scene-context-aware indoor object selection and movement in vr. In *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 235–244. IEEE, 2021.

[249] R. Wang, S. Paris, and J. Popović. 6d hands: Markerless hand-tracking for computer aided design. In *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST '11, p. 549–558. Association for Computing Machinery, New York, NY, USA, 2011. doi: 10.1145/2047196.2047269

[250] X. Wang, L. Besançon, D. Rousseau, M. Sereno, M. Ammi, and T. Isenberg. Towards an understanding of augmented reality extensions for existing 3d data analysis tools. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–13. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376657

[251] Y. Wang, Y. Hu, and Y. Chen. An experimental investigation of menu selection for immersive virtual environments: fixed versus handheld menus. *Virtual Reality*, 25:409–419, 2021.

[252] Y. Wang and R. Kopper. Efficient and accurate object 3d selection with eye tracking-based progressive refinement. *Frontiers in Virtual Reality*, 2:607165, 2021.

[253] C. Ware and K. Lowther. Selection using a one-eyed cursor in a fish tank vr environment. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 4(4):309–322, 1997.

[254] M. Weise, R. Zender, and U. Lucke. How can i grab that? solving issues of interaction in vr by choosing suitable selection and manipulation techniques. *i-com*, 19(2):67–85, 2020.

[255] R. Weller, W. Wegele, C. Schröder, and G. Zachmann. Lenselect: Object selection in virtual environments by dynamic object scaling. *Frontiers in Virtual Reality*, 2:684677, 2021.

[256] S. White, D. Feng, and S. Feiner. Interaction and presentation techniques for shake menus in tangible augmented reality. In *2009 8th IEEE International Symposium on Mixed and Augmented Reality*, pp. 39–48, 2009. doi: 10.1109/ISMAR.2009.5336500

[257] S. White, D. Feng, and S. Feiner. Poster: Shake menus: Towards activation and placement techniques for prop-based 3d graphical menus. In *2009 IEEE Symposium on 3D User Interfaces*, pp. 129–130, 2009. doi: 10.1109/3DUI.2009.4811220

[258] D. Wolf, J. J. Dudley, and P. O. Kristensson. Performance envelopes of in-air direct and smartwatch indirect control for head-mounted augmented reality. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 347–354, 2018. doi: 10.1109/VR.2018.8448289

[259] D. Wolf, J. Gugenheimer, M. Combosch, and E. Rukzio. Understanding the heisenberg effect of spatial interaction: A selection induced error for spatially tracked input devices. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, p. 1–10. Association for Computing Machinery, New York, NY, USA, 2020. doi: 10.1145/3313831.3376876

[260] J. Wonner, J. Grosjean, A. Capobianco, and D. Bechmann. Starfish: a selection technique for dense virtual environments. In *Proceedings of the 18th ACM symposium on Virtual reality software and technology*, pp. 101–104, 2012.

[261] C.-M. Wu, C.-W. Hsu, and S. Smith. A virtual reality keyboard with realistic key click haptic feedback. In *HCI International 2015-Posters' Extended Abstracts: International Conference, HCI International 2015, Los Angeles, CA, USA, August 2–7, 2015. Proceedings, Part I*, pp. 232–237. Springer, 2015.

[262] F. Wu, Q. Zhou, K. Seo, T. Kashiwagi, and S. Fels. I got your point: An investigation of pointing cues in a spherical fish tank virtual reality display. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1237–1238, 2019. doi: 10.1109/VR.2019.8798063

[263] C. Xu, M. Zhou, D. Zhang, W. Shui, and Z. Wu. Guidance rays: 3d object selection based on multi-ray in dense scenario. In *Proceedings of the 12th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry*, VRCAI '13, p. 91–100. Association for Computing Machinery, New York, NY, USA, 2013. doi: 10.1145/2534329.2534347

[264] C. Xu, M. Zhou, D. Zhang, W. Shui, and Z. Wu. Guidance rays: 3d object selection based on multi-ray in dense scenario. In *Proceedings of the 12th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry*, pp. 91–100, 2013.

[265] M. Yano, T. Itoh, Y. Tanaka, D. Matsuoka, F. Araki, T. Czauderna, and K. Stephens. Viewpoint selection for shape comparison of mode water regions in a vr space. In *2019 23rd International Conference Information Visualisation (IV)*, pp. 106–111, 2019. doi: 10.1109/IV.2019.00027

[266] X. Yi, Y. Lu, Z. Cai, Z. Wu, Y. Wang, and Y. Shi. Gazedock: Gaze-only menu selection in virtual reality using auto-triggering peripheral menu. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 832–842, 2022. doi: 10.1109/VR51125.2022.00105

[267] X. Yi, L. Qiu, W. Tang, Y. Fan, H. Li, and Y. Shi. Deep: 3d gaze pointing in virtual reality leveraging eyelid movement. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*, UIST '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3526113.3545673

[268] X. Yi, L. Qiu, W. Tang, Y. Fan, H. Li, and Y. Shi. Deep: 3d gaze pointing in virtual reality leveraging eyelid movement. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*, pp. 1–14, 2022.

[269] J. Yin, C. Fu, X. Zhang, and T. Liu. Precise target selection techniques in handheld augmented reality interfaces. *IEEE Access*, 7:17663–17674, 2019.

[270] Q. You, J. Lv, Y. Li, Y. Jin, and Z. Zhao. Small target selection model in virtual reality based on fitts' law. *Chinese Journal of Engineering Design*, 26(4):416–422, 2019.

[271] T. S. Young, R. J. Teather, and I. S. MacKenzie. An arm-mounted inertial controller for 6dof input: Design and evaluation. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 26–35. IEEE, 2017.

[272] D. Yu, H.-N. Liang, F. Lu, V. Nanjappan, K. Papangelis, and W. Wang. Target selection in head-mounted display virtual reality environments. *J. Univers. Comput. Sci.*, 24(9):1217–1243, 2018.

[273] D. Yu, H.-N. Liang, X. Lu, T. Zhang, and W. Xu. Depthmove: Leveraging head motions in the depth dimension to interact with virtual reality head-worn displays. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 103–114, 2019. doi: 10.1109/ISMAR.2019.00-20

[274] D. Yu, H.-N. Liang, X. Lu, T. Zhang, and W. Xu. Depthmove: Leveraging head motions in the depth dimension to interact with virtual reality head-worn displays. In *2019 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 103–114. IEEE, 2019.

[275] D. Yu, Q. Zhou, J. Newn, T. Dingler, E. Velloso, and J. Goncalves. Fully-occluded target selection in virtual reality. *IEEE transactions on visualization and computer graphics*, 26(12):3402–3413, 2020.

[276] D. Yu, Q. Zhou, B. Tag, T. Dingler, E. Velloso, and J. Goncalves. Engaging participants during selection studies in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 500–509, 2020. doi: 10.1109/VR46266.2020.00071

[277] J. E. Yu and G. J. Kim. Blurry (sticky) finger: Proprioceptive pointing and selection of distant objects for optical see-through based augmented reality. In *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR-Adjunct)*, pp. 336–337, 2016. doi: 10.1109/ISMAR-Adjunct.2016.0109

[278] H. Yuan, J. Cálić, and A. Kondoz. How do users select stereoscopic 3d content? In *2012 3DTV-Conference: The True Vision - Capture, Transmission and Display of 3D Video (3DTV-CON)*, pp. 1–4, 2012. doi: 10.1109/3DTV.2012.6365472

[279] M. A. Zayer, S. Tregillus, and E. Folmer. Pawdio: Hand input for mobile vr using acoustic sensing. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, CHI PLAY '16, p. 154–158. Association for Computing Machinery, New York, NY, USA, 2016. doi: 10.1145/2967934.2968079

[280] F. Zhang, K. Katsuragawa, and E. Lank. Conductor: Intersection-based bimanual pointing in augmented and virtual reality. *Proc. ACM Hum.-Comput. Interact.*, 6(ISS), nov 2022. doi: 10.1145/3567713

[281] J. Zhi, R. Xie, H. liu, X. Wang, G. Yang, P. Peng, X. Luo, and Y. Chen. A survey of interactive technology in augmented reality. In *2020 2nd International Conference on Information Technology and Computer Application (ITCA)*, pp. 101–104, 2020. doi: 10.1109/ITCA52113.2020.00028

[282] Q. Zhou, G. Fitzmaurice, and F. Anderson. In-depth mouse: Integrating desktop mouse into virtual reality. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*, CHI '22. Association for Computing Machinery, New York, NY, USA, 2022. doi: 10.1145/3491102.3501884

[283] X. Zhou, H. Qin, W. Xiao, L. Jia, and C. Xue. A comparative usability study of bare hand three-dimensional object selection techniques in virtual environment. *Symmetry*, 12(10):1723, 2020.

[284] D. Zielinski, B. Macdonald, and R. Kopper. Comparative study of input devices for a vr mine simulation. In *2014 IEEE Virtual Reality (VR)*, pp. 125–126, 2014. doi: 10.1109/VR.2014.6802083

[285] D. J. Zielinski, H. M. Rao, M. A. Sommer, and R. Kopper. Exploring the effects of image persistence in low frame rate virtual environments. In *2015 IEEE Virtual Reality (VR)*, pp. 19–26, 2015. doi: 10.1109/VR.2015.7223319

[286] Q. Zou, H. Bai, Y. Zhang, G. Lee, F. Allan, and B. Mark. Tool-based asymmetric interaction for selection in vr. In *SIGGRAPH Asia 2021 Technical Communications*, SA '21 Technical Communications. Association for Computing Machinery, New York, NY, USA, 2021. doi: 10.1145/3478512.3488615

[287] E. Zudilova-Seinstra, P. Sloot, P. de Koning, A. Suinesiaputra, R. van der Geest, and J. Reiber. Exploring 2d/3d input techniques for medical image analysis. In *2009 Second International Conference in Visualisation*, pp. 147–152, 2009. doi: 10.1109/VIZ.2009.18

[288] K. Özacar, J. D. Hincapié-Ramos, K. Takashima, and Y. Kitamura. 3d selection techniques for mobile augmented reality head-mounted displays. *Interacting with Computers*, 29(4):579–591, 2017. doi: 10.1093/iwc/iww035