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Object Selection and Manipulation in VR Headsets: Research Challenges, Solutions, and Success Measurements

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Object selection and manipulation are the foundation of VR interactions. With the rapid development of VR technology and the field of virtual object selection and manipulation, the literature demands a structured understanding of the core research challenges and a critical reflection of the current practices. To provide such understanding and reflections, we systematically reviewed 106 papers. We identified classic and emerging topics, categorized existing solutions, and evaluated how success was measured in these publications. Based on our analysis, we discuss future research directions and propose a framework for developing and determining appropriate solutions for different application scenarios.

CCS Concepts: • **Human-centered computing** → **Virtual reality**;

Additional Key Words and Phrases: Virtual reality, 3D user interfaces, selection and manipulation

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1 Introduction

Object selection and manipulation are canonical interactions in **virtual reality (VR)** systems [13, 21]. Users perform selections to identify the target of interest (e.g., menus, buttons, digital contents, 3D objects) and execute manipulations, including translation, rotation, and scaling, to transform the target into a desired configuration. Interacting with VR headsets fundamentally differs from desktops and touchscreens, because users are fully immersed in 3D digital spaces with co-located virtual objects. Consequently, they can observe a target from different angles, touch, grab, point, pull, push, and even squeeze objects. Because of this significant difference in experiencing the 3D world, VR headsets require unprecedented, new ways of interaction.

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Through more than 50 years of development of 3D interactions, originating from Sutherland's work on determining the viewing angle through head orientations in 1968 [74, 157], a multitude of solutions has been proposed for virtual object selection and manipulation. These solutions range from artifact inventions to empirical studies [9, 122, 161], span across interaction techniques and devices to predictive models [9, 54, 140, 182], and extend over user input and feedback mechanisms [7, 37, 81, 159]. With the rapid development of selection and manipulation solutions, it is crucial to step back and reflect on a few open questions relevant to the field regarding "where" we are going, "how" we are doing it, and "what" we can improve.

These open questions include: (1) What core challenges in VR selection and manipulation have researchers been trying to address? Are there new challenges emerging with the development of technology? (2) What are the state-of-the-art solutions for these challenges? Why are these solutions considered successful in solving the challenge? (3) What are the future directions of the research field? What are the criteria for determining a "better" interaction? With a proliferation of innovations within a brief timeframe, the current literature demands an in-depth discussion and reflection on these questions, which are critical to determining the backbone topics and emerging trends from scattered endeavours and ensuring the robustness and validity of research practices [84].

To remedy this situation, we conducted a systematic literature review of 106 publications on object selection and manipulation in VR headsets. We identified eight research challenges that the literature has been tackling, including classic ones such as the complexity in 3D interaction scenarios (e.g., small, far away, occluded, out-of-view targets) and emerging trends such as context integration and collaborative manipulation, as well as existing solutions to these challenges. Further, we summarised nine success measurements used by previous research when resolving the challenges. These success measurements allow us to assess current practices and identify potential issues. For example, we found few studies evaluating how new interaction techniques might reshape users' selection or manipulation strategies, raising questions regarding the long-term adaptation of the techniques. Next, we reflect upon the "ultimate" VR selection and manipulation solutions the community is working towards and offer recommendations for further research, such as ensuring the generalisability of the study results. We propose a framework for developing and determining appropriate solutions for application scenarios. Finally, we summarise our recommendations regarding research practices and directions for future studies.

2 Scope, Related Surveys, and Contributions

2.1 Scope and Definitions

This work focuses on "*object selection and manipulation in VR headsets.*" This section describes our scope and clarifies the inclusion and exclusion criteria.

2.1.1 Object Selection and Manipulation. Object selection encompasses identifying, pointing, and acquiring one or multiple objects from available objects. Object manipulation concerns the further actions available for handling the selected object, which includes positioning (changing object position), rotating (changing object orientation), and scaling (adjusting object size) [74]. In this work, we focus on manipulations that preserve the shape of objects (i.e., spatial rigid object manipulation [74]). Further, we focus on the selection and manipulation of general virtual objects rather than solutions developed for selecting a specific type of object (e.g., key selection in text entry [151], location selection for teleportation [43]). We did not include travel or wayfinding techniques, as they often lead to changes of user's positions, which may lead to entirely different challenges than selection and manipulation (e.g., presence and VR sickness) [2, 74, 95].

2.1.2 VR Headsets. This work focuses on VR technology that immerses users in a computer-synthesised virtual environment [103]. The challenges and solutions for selection and manipulation can be different in other immersive technologies, such as AR and MR, because of the presence of real-world objects [152]. Further, we focus on **head-mounted/worn displays** (**HMD/HWD**, or more colloquially, VR headsets), which means that the visual display devices should be coupled to the user's head. Therefore, stationary VR displays (i.e., displays that do not move with the user), such as tabletop VR displays and CAVEs, which afford different interaction capabilities from VR headsets, are out of the scope of this research.

2.2 Related Surveys

Several related surveys aim to develop taxonomies for 3D selection and manipulation techniques in the literature. Dang's 2007 review [27] provides a chronological view of 3D pointing techniques. It classifies them based on 3D pointer- or selection ray-based control as well as how pointing is enhanced (e.g., reducing cursor movement distance, increasing target size, or both). Argelaguet and Andujar's 2013 survey [5] not only categorises the techniques based on their intrinsic characteristics (e.g., selection tool types and how a user controls the tool) but also covers human pointing models and factors that may influence user performance in selection tasks (e.g., target geometry and object density). LaViola et al.'s 2017 book [74] (which updates Bowman et al.'s 2005 book [21]) discusses techniques for 3D selection and manipulation based on a classification of their metaphors: grasping, pointing, surface, indirect, bimanual, and hybrid. Weise et al.'s 2019 paper [167] also classifies 3D selection and manipulation techniques according to their different characteristics (e.g., metaphor, degree-of-freedom, reference frame). Moreover, Mendes et al.'s 2019 survey [99] reviews 3D virtual object manipulation techniques, from desktops to immersive environments. It proposes a taxonomy based on environment properties and types of transformations. Overall, these taxonomies provide structured ways of viewing the 3D interaction techniques in the literature. In contrast, our work does not classify interaction techniques or task scenarios.

More relevant to our work are surveys that aim to identify design challenges with 3D interfaces and research trends for future work. Hinckley et al.'s 1994 survey [57] synthesises design issues and potential solutions for developing effective free-space 3D user interfaces. For example, they identify that users may have difficulty understanding 3D space and offer solutions such as multi-sensory feedback to resolve this issue. They are also concerned about issues related to, for instance, dynamic target acquisition and ergonomics. Hand's 1997 survey [51] overviewed state-of-the-art 3D interaction techniques at that time and highlighted the research opportunity of usability testing for future work. Similar to these surveys, our work aims to determine research challenges and solutions and identify future research directions. We achieved this through a systematic literature review to provide an updated and more comprehensive view of the VR research landscape, given the recent advancement of VR headsets.

Bergström et al.'s 2021 review [13] derives guidelines on how to conduct and report object selection and manipulation studies in VR. Task types, experimental settings, target parameters, and dependent variables of such studies were analysed in detail. Bergström et al.'s work aims to inform the design of future research studies. In contrast, our work seeks to understand the research field of VR selection and manipulation regarding "where" we are going, "how" we are doing it, and "what" we can improve. Other surveys inform the analysis in this article but address a different subject [1]. These include but are not limited to, a review of mid-air interaction [70], a survey of interaction with large displays [4], and a review on distant object selection methods [79].

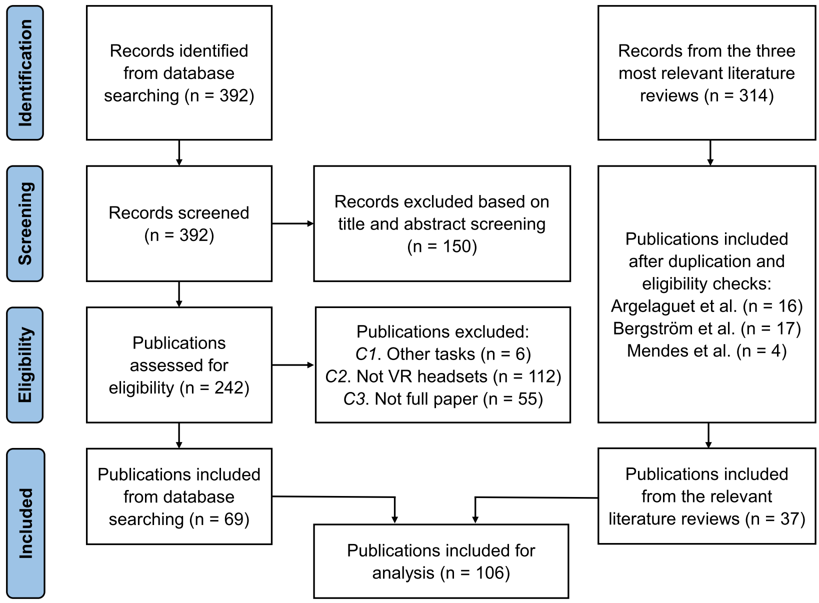

Fig. 1. PRISMA flow diagram of our systematic review.

2.3 Contributions

This review focuses on determining (1) the primary challenges research papers aimed to solve in VR object selection and manipulation research and (2) the existing solutions to these challenges. With a surge in the number of novel developments over a short duration, it is essential to summarise scattered research endeavours and analyse critical research challenges and the corresponding state-of-the-art. This helps us reflect on the practices and identify the backbone topics and the emerging trends in the research field to better inform its future development. Our results should guide newcomers to the research field and offer new, structured perspectives for senior researchers.

Further, our work identifies three future research directions by evaluating how researchers measure their success under each research challenge. This allows us to assess the validity and robustness of the current practices and diagnose potential problems with the existing measurements (e.g., whether the selected measurements will lead us to solve the challenge). The results will aid future researchers in this field to better approach the research challenges with more appropriate measurements. We open-source our coding manual for future research to expand upon.

3 Methodology

We followed the PRISMA guidelines [107] to select relevant publications for analysis. Our initial information sources of publications came from online databases and the most pertinent literature review papers. We then applied the four-step process (identification, screening, eligibility, inclusion) to derive our final corpus. Figure 1 gives an overview of this filtering procedure.

3.1 Systematic Query Searches within Online Databases

We first performed systematic queries in online databases, including ACM Digital Library, IEEE Xplore, Wiley Online Library, Scopus, Taylor & Francis Online, and Springer Link to identify relevant, high-impact papers on object selection and manipulation in VR headsets. The publication venues included in the search were CHI, UIST, VRST, SUI, CSCW, Ubicomp, DIS, IUI, TOG, IMWUT, PACM HCI, TOCHI, IEEE VR (including 3DUI), ISMAR, TVCG, Computer Graphics Forum, IJHCS, Computer & Graphics, IJHCI, and Springer VR. These venues were selected based on their relevance to the field of **Human–Computer Interaction (HCI)** and VR, as well as their impact, according to Google Scholar Metrics (under the categories of HCI and Computer Graphics).

To identify publications that are primarily relevant to object selection and manipulation in VR headsets, we used "*selection*," "*manipulation*," and "*virtual reality*" as our initial search terms in publication titles and iteratively derived their synonyms based on the literature present in the publication venues mentioned above. The new terms identified were "*pointing*," "*acquisition*," "*VR*," "*3D*," and "*immersive*." We did not include the term "*interact*" (as in "object interaction") or search the publication abstracts for keywords, as they returned a large number of irrelevant records from the online databases. We documented our detailed search process in our supplementary material. A simplified example query in the ACM Digital Library, without including the publication venues, is:

```
Title:((acqui* OR point* OR select* OR manipulat*) AND (virtual OR VR OR 3D OR
Immers*))
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Here, * denotes any number of unknown characters (wild cards). We were thus able to include other word forms such as "*manipulate*," "*manipulating*," and "*manipulation*." The word "*virtual*" was used to capture similar wordings of virtual reality environments such as "*virtual environment*" and "*virtual object manipulation*." In total, we obtained 392 records from searching the databases.

Upon obtaining these initial records, we screened their titles and abstracts to exclude papers irrelevant to our exploration (e.g., constructing a 3D point cloud). This process left us with 242 publications. Next, we assessed the full text of these publications for eligibility according to three criteria: (1) not about object selection and manipulation; (2) not in VR headsets; (3) not a full paper. The first two criteria were based on the scope of this research. We also excluded posters and extended abstracts, as they usually have a different level of maturity than full papers. At the end of this filtering procedure, we were left with 69 publications.

3.2 Records from Relevant Literature Reviews

We also examined all references in the three most relevant literature review papers to extract further papers relevant to our topic. This was to ensure that we included impactful papers that were not published in the selected publication venues or did not use our keywords in the title (e.g., object *interaction* instead of *selection* or *manipulation*). The most relevant review papers we used were Argelaguet and Andujar's survey on 3D object selection techniques for virtual environments in 2013 [5], Bergström et al.'s papers on guidelines for evaluating VR object selection and manipulation in 2021 [13], and Mendes et al.'s survey on 3D virtual object manipulation in 2019 [99]. We assessed the papers' titles and full texts to exclude less relevant papers using the same criteria and remove duplication in the collected papers. At the end of this process, we were left with 37 publications.

3.3 Dataset and Coding Process

We collected 106 publications (69 from online database query searches and 37 from the three most relevant literature reviews) as the corpus for further analysis. With this corpus, we first coded the challenges, research goals, proposals/methods, and measurements of success in text fields by collecting quotations from the papers. We then iteratively defined 26 challenge types across the papers and distilled eight core challenges. We also coded relevant information such as contribution types, solution types, study types, and success measurement types categorically by referencing the classifications in previous research [59, 76] and iteratively defining them. Some papers had made multiple contributions and proposed various solutions, and we thus distinguished their primary

Fig. 2. Number of publications under the contribution types proposed by Wobbrock and Kientz [175].

and secondary contributions and solutions in our coding. More details about the preliminary and final classifications can be found in our coding manual.

4 Overview of Contribution Types

We investigated the contribution types of the 106 publications in our corpus according to Wobbrock and Kientz taxonomy [175]. Figure 2 summarises the results. A significant portion of the papers contributed new *artefacts* (42 papers, 39.6%), including, for example, new interaction techniques for occluded target selection [143, 163, 186], systems for grasping rendering [30, 114], and novel haptic devices [7, 37, 78]. Another mainstream of the papers focused on *empirical* contributions (49 papers, 46.2%), where user studies were carried out to evaluate or compare technological solutions [71, 122], fine-tune design parameters [137, 170], investigate the effects of a factor [10, 69], or explore design possibilities [82, 178]. There were four *methodological* papers (3.8%) on standardising the research practices in VR object selection and manipulation [13, 19, 20, 130]. Eight were *survey* papers (7.5%) that have provided a new taxonomy of the techniques [27, 99] or intended to answer specific research questions [32]. Three papers (2.8%) have a *theoretical* emphasis on initiating new design spaces or frameworks that could motivate new interaction techniques [105, 124, 153]. Note that we classified qualitative models, such as models that predict selection endpoints [54, 182], as either empirical or artefact contributions. While these models may have predictive power, they do not aim to provide a systematic set of statements that explains the mechanism (e.g., why the endpoints distribute in a certain way), which is an essential component of a theoretical contribution [134]. None of the papers had the primary contribution of datasets or opinions. A geographical distribution analysis of the authors who have contributed to these published papers is included in Appendix A for interested readers.

5 Research Challenges and Existing Solutions

We identified eight research challenges and their corresponding solutions for VR object selection and manipulation research. We iteratively defined these eight core challenges by surveying the key problems and research goals. Throughout this process, we wanted to capture research challenges that have attracted substantive attention from the community. We were also interested in identifying emerging topics with a limited number of publications that may still be promising for future research. Table 1 summarises these research challenges and solutions.

We note that our categorisation of the research challenges is not mutually exclusive, and many papers presented within each section may tackle one or more challenges. Our goal was to capture and classify the primary obstacle that a research paper aimed to resolve and the main solution offered by the paper. With this process, we can see the representative themes in the VR selection and manipulation literature. We also note that we excluded general surveys that do not tackle

Table 1. A Summary of Research Challenges and Solutions on VR Object Selection and Manipulation

1	**Complexity in 3D Interaction Scenarios** Challenge - Selecting and manipulating 3D virtual objects in VR headsets can be challenging, because the interaction scenarios may contain small, far away, occluded, out-of-view, and multiple targets. The tasks may require precise control. Solution - Optimising selection and manipulation designs for simple and more complex (e.g., distant, occluded, out-of-view targets) VR scenarios.
2	**Underexplored Interaction Spaces and Factors** Challenge - Understanding new opportunities (i.e., design spaces or ways of interaction) and considerations (i.e., factors that influence user behaviour or responses) of 3D user interfaces. Solution - Conducting usability studies on (1) possible ways to offer new interaction (e.g., 3D eyes-free selection) and (2) scrutinising how specific factors (e.g., the presence of multimodal feedback and visual avatar) influence user performance, experience, and behaviour.
3	**Unknown Comparative Usability** Challenge - The lack of understanding or guidelines of the relative usability between different solutions to inform "which method(s) to choose under a given situation." Solution - Conducting usability studies on comparing and benchmarking alternative choices of devices (e.g., game controller vs. 3D pen-like device), modalities (e.g., gaze vs. hand vs. head), and techniques (e.g., Raycasting vs. Virtual Hand).
4	**Ergonomic Issues: Workload and Fatigue** Challenge - Fatigue from extended 3D interactions and physical constraints in users' interaction space. Solution - Developing techniques that fulfil users' space and comfortable requirements.
5	**Imprecise Rendering of Visual and Haptic Realism** Challenge - Enabling more realistic and believable visual and haptic rendering during object selection and manipulation under hardware limitations and form factor constraints. Solution - (1) Proposing algorithms for realistic hand rendering, (2) building devices for simulating different haptic features (e.g., textures, shapes, and stiffness), and (3) conducting usability studies to explore methods that can improve perceived visual and haptic realism.
6	**Underdeveloped Evaluation Methodology** Challenge - Standardising the practices of evaluating selection and manipulation solutions to allow the generalisation of results across studies. Solution - Building relevant testing framework, testbeds, and guidelines.
7	**Limited Support for Collaborative Object Manipulation** Challenge - Simultaneous manipulation of a virtual object with multiple users. Solution - Building framework and techniques to enable simultaneous object manipulation.
8	**Context Integration and Workflow Optimisation** Challenge - Integrating selection and manipulation into the "broader" context and workflow. Solution - Developing techniques that consider the context and simplify the workflow.

specific challenges (but summarise them or their solutions) [5, 27, 51, 57, 70, 99, 156] and an early programming implementation of basic interaction techniques [135] in this analysis.

5.1 Complexity in 3D Interaction Scenarios

Though VR technology may create unprecedented opportunities for new types of interaction, developing appropriate 3D user interfaces for selection and manipulation is not trivial. Historically, there have been two seminal selection and manipulation techniques: Virtual Hand and Raycasting [5, 74]. Virtual Hand creates a virtual replica of users' physical hands in the VR space, and the user can use the virtual hands to grab and manipulate virtual objects. Raycasting emanates a virtual ray into the environment from (typically) the physical hand position, and the user can control the ray to point and interact with objects. These techniques are simple, straightforward, and intuitive for 3D interaction and have been employed in many off-the-shelf applications.

However, the literature has also pointed out known usability issues with these techniques. Performing actions in 3D space is inherently difficult [55, 57]. Simple techniques such as Virtual Hand and Raycasting can be imprecise and inefficient [5, 74], especially when users cannot feel the physical properties (e.g., shapes, textures, weights) of virtual objects. For example, inputs such as a button click could disturb the position of the input device and result in a different selection point (i.e., the Heisenberg effect) [176].

Meanwhile, VR interaction can be complex because of the added depth dimension. For example, interaction scenarios such as immersive data analytics [92], medical training [138], and interior design [66] may involve complicated visualisations. Therefore, targeted objects of interest can be small, far away, occluded, off-screen, and even moving. It is challenging to acquire and manipulate such targets with Virtual Hand and Raycasting. In other application scenarios like 3D modelling [68], the task may require precise interaction techniques. While Virtual Hand and Raycasting may work fine for simple interactions with unoccluded, properly sized buttons, menus, and virtual objects, because of the aforementioned usability issues, they may not be sufficient for more complex scenarios. Therefore, papers under this theme aim to optimise selection and manipulation interfaces for simple and more complex 3D VR interaction scenarios.

In the following, we point to 34 papers that address complexity in 3D interaction scenarios. Among the selected papers, most of them (27 papers, 79.4%) primarily contributed new artefacts, including (1) *interaction techniques*, the fusion of input and output for users to complete tasks in human-computer dialogues [39, 160]; (2) *devices*, the hardware pieces employed by users to communicate with a computer [23, 58, 90]; and (3) *models*, the computational assistance that improves the usability of an interface through user behaviour prediction [54]. The remaining papers (7 papers, 20.6%) primarily presented empirical contributions. Empirical user studies were carried out to derive (1) *design knowledge*, the body of knowledge that can be used in similar application scenarios, e.g., the advantages and disadvantages of a technique [161]; (2) *design recommendations and guidelines*, the explicit set of "rules" that inform future designs [101, 159, 183]; (3) *desired design parameters*, the setting of design parameters where the proposed solution can be the most useful [81]; and (4) *models* [182], verbal or mathematical representations that describe and predict the characteristics of human-computer interactive dialogues [90]. We elaborate on existing solutions for VR selection and manipulation as follows.

5.1.1 Selection Approaches. Many proposed techniques improved the selection speed and accuracy by adjusting the criteria of how the selection of a target is determined. Rather than requiring a tiny virtual pointer to be exactly "on" the targeted object, an enhanced technique may select the closest object to the pointer [9, 154], scale up the cursor size [40, 87], predict the intended target [54, 182], or introduce crossing-based [159] or multi-step selection techniques [100]. To select objects with different depths, techniques also added an extra dimension of movement (moving along the depth dimension) to the Raycasting pointer [9] or distributed multiple 3D cursors across the space [140]. Moreover, they incorporated multi-modality support with pen-based input that leveraged dexterous finger movements [81] and synergetic gaze and head-based input [144].

Other selection techniques have been developed to handle more complex 3D VR environments that contain distant, occluded, out-of-view, or multiple targets. While a user can only select objects within the arm-reach distance with Virtual Hand, assistant techniques may extend the movement of the virtual hand [18, 127] or create a reachable replica of the virtual environment or its elements [123, 156]. For partially or fully occluded targets, existing techniques leveraged disocclusion visualisations (e.g., making distractors transparent or translating candidate objects into new locations) to identify the target [163, 186]. Techniques also modified selection mechanisms (e.g., gaze-based outline pursuits [143], Bézier curve-modified selection ray [38]) to acquire such occluded targets. For an out-of-view target, proposed techniques can guide the user towards its location through, for example, vibrotactile cues [73]. If there were multiple targets in the scene, then techniques could create a selection volume via, for example, a volumetric cube, a lasso, or a virtual tablet and further progressively refine the selection [64, 108, 155].

5.1.2 Manipulation Approaches. The literature presented two main methods to improve the usability of VR object manipulation: **degree-of-freedom (DoF)** separation and **control-display ratio (CD ratio)** adjustment. DoF separation-based techniques reduced the number of DoFs being controlled simultaneously compared to Virtual Hand (which has three axes for translation, rotation, and scaling). For example, researchers adapted 3D virtual widgets similar to those used in desktop CAD software (e.g., Unity, Blender) for VR headsets [22, 77, 101, 102]. They further enabled user-defined 3D anchor points or transformation axes [45, 102]. CD ratio adjustment-based techniques dynamically increased or decreased the movements of the virtual hand compared to the corresponding physical hand [102, 127]. For example, scaling up the movement may allow coarse, rapid manipulation, while scaling it down may enable more fine-grained transformation [41, 42]. Additionally, previous research has also combined Virtual Hand and Raycasting [148, 161], designed finger gestures for rotation control [148], allowed users to impersonate an under-manipulated object [162], and incorporated gaze input into the manipulation process [183].

5.2 Underexplored Interaction Spaces and Factors

One primary goal of HCI research is to understand users' needs towards computing interfaces and map out new spaces of designs. Shifting from 2D interfaces such as PC screens and tablets, many research questions exist on how to best leverage the 3D virtual space for interactions [74]. Specifically, there is a need to understand the new opportunities (i.e., design spaces or ways of interaction [50, 53]) and considerations (i.e., factors that may influence user behaviour or responses) that 3D interfaces may bring. Therefore, determining underexplored interaction spaces and factors is another major challenge many papers aimed to resolve in the literature.

Twenty-eight papers in our corpus aimed to explore new interaction spaces and factors that may enhance VR selection and manipulation. The majority (24 papers, 85.7%) focused on empirical contributions through discovering design knowledge, recommendations and guidelines, desired parameters, and models. There was one survey paper on conducting a meta-analysis to derive guidelines [32], two theoretical papers about a framework [105] and a conceptual model [153], and one artefact paper on a novel device to offer new ways of interaction [49].

A collection of papers examined new design spaces to offer interaction. They considered, for example, the feasibility of eyes-free target acquisition [105, 177, 178, 190], the practicability of freehand pointing without a selection ray [26, 97], and the usefulness of modifying control-to-display mappings (input scale [44, 72, 170], direct vs. indirect input [72], and cursor offset [80]). They also tried to understand how users prefer to select and manipulate objects in VR [116, 172] and investigated the locations of providing 3D virtual interfaces (e.g., arm-anchored [82], smartphones [72], fovea and periphery regions [67], user's own body [105], and a display attached to the face [49]) and the spatial and temporal aspects of selection [153].

Another set of works scrutinised how specific factors presented in user interfaces may influence performance, kinematic features, and user perception during VR selection and manipulation tasks. These factors include multimodal feedback [6], interaction fidelity (e.g., widgets vs. physically grabbing items) [136], the presence of virtual avatar [29, 32], the aptitude and experience of individuals [171, 173], perception of redirection [28], the absence of haptic feedback during VR manipulation [88], and object features such as size and distance (e.g., References [171, 182]). Other works explored the impact of device-related factors on VR selection, including vergence-accommodation conflict [10], stereo deficiency [11], and jitter of input device [12].

5.3 Unknown Comparative Usability

While new solutions have been developed, their comparative usability is not always clear, such as effectiveness, efficiency, and satisfaction [59]. The lack of understanding or guidelines of the relative usability makes it hard to choose a more suitable approach for different applications. To solve this challenge, some research is dedicated to comparing and benchmarking the usability among diverse VR selection and manipulation solutions. These studies aim to inform the design decision of "*which method(s) to choose under a given situation.*"

While comparing usability among different solutions is common in the relevant literature, the unique point of the research studies summarised in this category is that they typically do not propose new interactions or explore new interaction spaces. In contrast, they leverage existing solutions and compare them under new conditions.

We identified 15 papers in our corpus where the primary goal was not to develop new methods but to perform rigorous empirical evaluation studies that compare choices of devices [3, 17, 71, 106, 122], modalities [25, 34, 61, 106, 119, 131], and techniques [69, 94, 128, 129, 166]. They were all empirical contributions, focusing on developing design knowledge, guidelines, and recommendations. For example, existing studies compared displays (e.g., VR, AR, and PC screen) and input devices (e.g., handheld controller, bare hand, 3D pen-like device, and mouse) for object selection and transformation tasks [3, 71, 122]. A few studies measured the performance of different input modalities (e.g., eye, hand, head, and muscle contraction) for VR object selection [25, 61, 119, 131]. They also analysed feedback modalities such as auditory and force and derived design guidelines based on the study results [34]. Moreover, researchers also conducted empirical studies to compare switchable vs. fixed DoF control during object manipulation [69], visualisation techniques for precise object alignment [94], and fixed vs. handheld menus for selection [166].

5.4 Ergonomic Issues: Workload and Fatigue

Many mid-air interactions can be cumbersome for prolonged interaction because of the gorilla arm effect—the fatigue caused by the weight of the arms while interacting in mid-air [16, 56]. Ergonomic assessments on workload and fatigue have been applied extensively to evaluate and compare different selection and manipulation approaches [13]. Measurements through self-reports (such as NASA-TLX [52] and Borg CR10 [15]) are often included in studies as accompanying metrics for usability. To improve VR interactions that involve large, cumbersome body movements and overlook the limits of a user's physical interaction space, comfort requirements, and mobility issues, recent research has been proposing designs explicitly to address this challenge [109, 168].

Our corpus presented two papers addressing ergonomic issues related to workload and fatigue during VR interaction. Both papers primarily contributed new interaction techniques, while one also proposed design recommendations [168]. Montano et al. [109] proposed an optimisation-based retargeting strategy to relocate visual targets to more convenient reaching positions. Wentzel et al. [168] investigated non-linear virtual hand amplification functions to improve arm ergonomics while maintaining body ownership. Both methods aimed to make the VR interaction experience more comfortable and accessible.

5.5 Imprecise Rendering of Visual and Haptic Realism

With advances in optics and audio technologies, current VR headsets can offer an improved sense of presence in simulated realities, creating a fully immersive experience [8]. However, realism often breaks when users attempt to grab and manipulate virtual objects: Their virtual hands/fingers can pass through the object [114], and they cannot "feel" the physicality of the object in the real world [137, 141]. For Virtual Hand-based selection and manipulation methods that mimic real-world experience, the challenge is to develop realistic and believable visual and haptic renderinging techniques under hardware limitations and form factor constraints.

We identified four papers on visually realistic grasping of objects during VR manipulation. Three were primarily artefact contributions on new rendering systems, and one was an empirical contribution that evaluated alternative visual representations. Oprea et al. [114] proposed a system that automatically fits a hand to the shape of virtual objects during grasping. Delrieu et al. [30], and Sorli et al. [149], realising there might be inherent mismatches in the tracked hand and the virtual hand during hand-object manipulation without an actual physical object, introduced strategies that balance between the tracked and the simulated hand to enable fine manipulation. Dewez et al. [31] considered visual realism of avatars when adjusting the CD ratio during selection and manipulation (e.g., Go-Go [127]) and examined dual representations of a user's virtual body.

Our corpus also included five papers on providing *active* or *passive haptics* to enable haptic renderings such as textures, shapes, stiffness, and weight of objects during VR manipulation. Four were artefact contributions on new haptic devices, and one was empirical contributions on determining design parameters for more believable haptics. A few papers focused on active haptic techniques that exert forces onto virtual contact areas through haptic devices to simulate a compelling interaction experience [7]. Schorr and Okamura [141] and Lee et al. [78] built wearable devices to trigger haptic feedback on users' fingertips. In contrast, others examined passive haptic approaches that leverage a pre-defined set of physical props as proxies of virtual objects. For instance, Arora et al. [7] used custom-designed LEGO bricks to simulate various object shapes. Feick et al. [37] further used composable shape primitives and connectors to simulate the haptic sensations of a complex virtual model. While providing a matching physical prop for every virtual object is not scalable, Samad et al. [137] created illusions of the changed weight of virtual objects with limited physical props by adjusting the CD ratio within an appropriate range.

5.6 Underdeveloped Evaluation Methodology

A valid and reliable evaluation methodology is the cornerstone for assessing the usefulness and effectiveness of a new method for selection and manipulation [175]. Results yielded under rigorous evaluation methodologies can accumulate replicable findings, provide design guidelines, and potentially enable the comparison of techniques across studies [13].

The initial obstacle of this space was to build a representative set of VR interaction tasks, task parameters, and evaluation metrics so the research findings can be generalised beyond a particular experimental setting [19, 20, 74, 130]. However, with the evolution of VR technology, the challenge shifted towards designing studies that may consider a variety of new, essential factors that are not covered in a canonical task setting while preserving generalisability [13, 187]. Ultimately, these methodological works aim to standardise the practices in technique evaluation [13].

Our corpus contained five papers on standardising evaluation methodologies of object selection and manipulation in VR. Four methodological contributions involved testbeds, frameworks, and design guidelines that inform how to conduct empirical studies. One empirical contribution investigated whether specific factors could influence the validity of user evaluations.

Poupyrev et al. [130] and Bowman et al. [19, 20] formalised early testbeds for technique evaluation. Poupyrev et al. [130] presented *VRMAT*, a testbed containing three basic interaction tasks (select, position, and orient) with their corresponding independent variables and evaluation metrics. Bowman et al. [19, 20] further suggested that an interaction task (e.g., colouring an object) can be broken down into several sub-tasks (e.g., selecting an object, selecting a colour, and applying a colour). Each sub-task can be achieved by various interaction techniques, which can be evaluated by manipulating important outside factors (such as task characters and environments). More recently, Yu et al. [187] investigated the potential issue of disengagement with long, repetitive selection experiments and evaluated motivational strategies to incentivise participants during such experiments. Bergström et al. [13] analysed research works in evaluating object selection and manipulation from 2000 to 2019 and proposed recommendations and checklists on task design and result reporting for guiding future studies.

5.7 Limited Support for Collaborative Object Manipulation

When multiple users collaborate in VR, a common need is to move and modify objects within the virtual space cooperatively [35, 133]. For example, users may need to assemble a complex object together [164], modify a 3D data visualisation concurrently for exploration [14, 33], and place digital furniture at different locations for configuration testing [133]. Existing research identifies the challenge of simultaneous manipulation of a virtual object with multiple users [75, 124, 125, 147, 164]. When two or more users want to manipulate the same virtual object, it is essential to determine who should control the object for better efficiency and user experience.

Our corpus captured two papers on providing simultaneous object manipulation in VR headsets. There was one theoretical contribution and one artefact contribution. Pinho et al. [124] introduced a conceptual framework (*Collaborative Metaphor*) that considers which input technique to use, how to combine them, and how to display a user's action to others in a collaborative task. They also presented interaction techniques that, for example, allowed collaborators to control different transformations (such as managing either translation or rotation). Wang et al. [164] proposed an interaction technique that determines the dominant manipulator based on a viewport quality function that examines quantities such as object visibility and distance of the target.

5.8 Context Integration and Workflow Optimisation

Although selecting or manipulating an object is typically treated as an individual task in research studies, they are associated with scene and interaction contexts in realistic applications. For example, a selected object may belong to a group of closely related objects, which are often manipulated together [165]. A manipulation gesture may result in multiple consequences, because the same gesture is used for several tasks [24, 91]. Integrating selection and manipulation techniques into the "broader" context and workflow is another challenge based on the literature.

We identified three recent papers that proposed new artefacts (specifically, interaction techniques) on this topic. Mardanbegi et al. proposed *EyeSeeThrough*, which simplifies the process of tool selection and application: Users can visually align a target object with the tool at the line-of-sight to apply the tool to the object, rather than performing a tedious two-step operation of first selecting the tool and then selecting the target [91]. Chen et al. proposed a technique that resolves ambiguous hand manipulation gestures (e.g., hand movements can either displace or stretch an object) with a pop-up menu that can be interacted with head gaze [24]. Wang et al. developed a method that considers scene context information, such as object semantics and interrelations when selecting or moving an object. For example, the technique can automatically adjust the yaw of a chair during translation to make it face a nearby table [165].

5.9 Summary Statistics

We analysed how the number of publications under each challenge changed over the years. The results are summarised in Figure 3. The total number of publications has significantly increased in recent years (since 2017), perhaps because of the advancements made in the off-the-shelf headsets and development kits such as Oculus CV1 and HTC VIVE headsets. Note that our literature review was initiated in early 2022, so limited publications were captured for this year.

The topics of complexity in 3D interaction scenarios, underexplored interaction spaces and factors, and unknown comparative usability have remained attractive and mainstream since the 1990s.

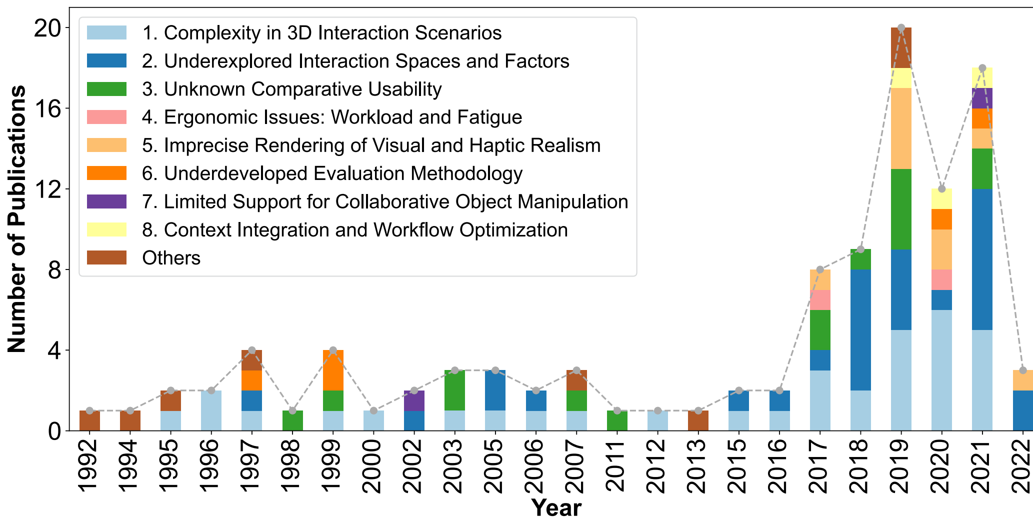

Fig. 3. Chronological depiction of the number of publications addressing proposed challenges, presented through a stacked bar chart. The dashed line signifies the annual total publication count.

There are also emerging themes where all relevant publications appear in more recent years. Researchers gained interest in resolving ergonomic issues related to workload and fatigue, rendering more precise and believable visuals and haptics, and integrating selection and manipulation techniques into a broader interaction context. One interesting observation is that the publications on evaluation methodology were present early in 1997 and 1999, remained silent between 2000 and 2019, and were picked up again more recently (2020 and 2021). Also, the topic of collaborative object manipulation appeared in 2002 and was continued in 2021.

6 Measuring Success

Based on the presented research challenges and solutions, we further investigated and reflected on how authors of the selected papers measure the success of their solutions. Based on the literature, we first categorised nine success measurements (effectiveness, efficiency, ergonomics, experience, robustness, versatility, realism, behaviour, and consistency). We then analysed how these measurements were applied in each research challenge.

Through this analysis, we aimed to answer three motivating questions: (1) Has the literature over-emphasised performance measurements such as task completion time and error rate to make a case for a successful solution? (2) Are the existing success measurements appropriate for the research challenges? (3) What should we expect about future selection and manipulation methods? The answers to these questions, as discussed in Section 7.2, allowed us to assess the validity of the current practices and identify potential problems in the field.

6.1 Measurements

We first summarised and categorised the success measurements used in the papers. During the iterative development process, we borrowed concepts from Hornbæk's work [59] on usability measurements while extending the original classifications (effectiveness, efficiency, and satisfaction) to a more detailed, domain-specific version with nine measurements. For example, we distinguished efficiency regarding completion time and workload into two usability measurements (efficiency and ergonomics) to improve the granularity. We also introduced new dimensions more relevant to VR selection and manipulation research, such as robustness and realism.

— *Effectiveness.* Effectiveness represents "the accuracy and completeness with which users achieve specific goals," as according to ISO 9241 [63]. Specific measures used in our corpus include error rates (e.g., percentage of incorrect selections [11, 87]), error distances or rotations (e.g., offsets between the target and the actual input [78, 97, 101, 164]), false positives/negatives (e.g., in a group selection scenario [108, 155]), and task completion (e.g., completion rates [42, 45]). They also involve prediction accuracy of a model [26, 54, 182] and may get incorporated in throughput measures [6, 61].
— *Efficiency.* The ISO 9241 (2018 version) defines efficiency as "resources used in relation to the results achieved" such as time, human effort, and materials [63]. To make it more specific to our tasks, we considered efficiency as the time cost associated with the results achieved. The typical measure in our corpus is task completion time (e.g., cursor movement time [122], selection time [187], manipulation time [30]). They also get involved in throughput measures [82].
— *Ergonomics.* While ergonomics is a broad term in certain contexts, we here restrict it to the physical or mental workload associated with the results achieved. Objective quantification (approximation) of ergonomics employed in our corpus include hand/arm movement distance [87, 183] and **RULA (rapid upper limb assessment)** score [109]. Subjective measures related to ergonomics contain questionnaire results from NASA-TLX [49], Borg CR10 [168], customised scales of fatigue and comfort [87, 122], and qualitative feedback [81].
— *Experience.* This encapsulates users' feelings and satisfaction when performing tasks with the evaluated solutions [58]. These data are normally collected from questionnaires. The measures include, but are not limited to, overall impression [37], general user experience [165, 186], satisfaction [61], preference [44, 105, 122], sense of control [45, 61], body ownership [29, 31, 78, 137, 168], ease-of-use [144, 161], fun [45, 101], perceived performance [72, 87, 162], perceived ease of learning [24, 41], perceived usability [94], intuitiveness [24, 87], sense of presence [77, 164], immersion [136], engagement [136], obtrusiveness [106, 186], and sickness [170, 178].
— *Robustness.* A robust solution remains useful under different testing conditions, especially if the solution has been evaluated to achieve good performance under more challenging scenarios. It can also mean that a derived conclusion performs consistently across multiple studies. For example, researchers have tried to evaluate their solutions under difficult scenarios (e.g., wider or untested conditions for a predictive model [182] and high occlusion scene [87, 143]) to test their robustness. They have also performed meta-analyses to determine robust conclusions [13, 32].
— *Versatility.* Versatility reflects whether a solution can be applied for a wide range of interaction scenarios or even enable new use cases. To demonstrate versatility, researchers often present a section of application scenarios in the paper (e.g., References [37, 165]). For instance, when introducing the haptic device *VirtualBricks* [7], the authors detailed example applications such as its use in first-person-shooter games, fishing, disco, and so on. Additionally, a framework or testbed may illustrate its versatility through sample techniques and use cases [20, 124, 130].
— *Realism.* Realism (sometimes dubbed as naturalness [30, 149]) is defined as how well the way of interacting with virtual objects corresponds to the way of interaction in the physical world. We consider it separately from experience measures, as it emphasises the cognitive judgment of physical-virtual mismatches more than the interaction experience itself. Realism is also different from body ownership, the psychological mapping of one's real body to a virtual body [146], and sense of embodiment, the illusion that the co-located virtual body

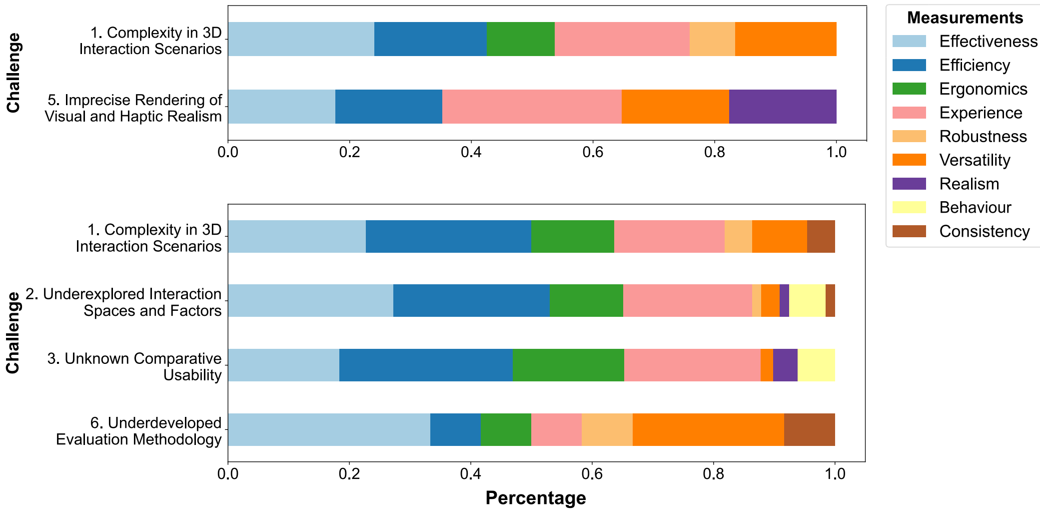

Fig. 4. Two percentage stacked bar charts showcasing the prevalence of success measurements being utilised to substantiate the usefulness of proposed solutions across artefact papers (top) and the likelihood of these measurements being applied in empirical, methodological, theoretical, or survey papers (bottom). Broader bars indicate a more widespread adoption of the respective measurement.

has effectively replaced their physical body [46]. Realism is typically assessed through customised scales [30, 106, 149], discrimination tasks (e.g., weight discrimination [137, 141]), or qualitative interview [137].

— *Behaviour.* User behaviours are likely to change if a new solution is adopted. Several papers have demonstrated that different approaches could influence interaction strategies [161, 183], movement profiles [6, 170, 182], and Fitts's law parameters [61, 159]. A few showed that their solutions could encourage positive behaviours in an interaction context. For example, the solutions can increase user participation [164], cursor speed [122], and maximum reach distance [31]. They can also decrease the number of iterations to complete a task [128], the number of target re-entries [10, 11], and the number of times that users press the trigger button [44].
— *Consistency.* Consistency refers to how measurements such as effectiveness, efficiency, ergonomics, and experience change over time. A few papers in our corpus have checked the performance of their solutions in prolonged interaction scenarios. They found the performance (e.g., completion time and error rates) could be influenced by learning/practicing [31, 159, 171], fatiguing, and disengagement [187].

6.2 How Solutions Address Each Research Challenge

We assessed how success measurements were used in each paper. In artefact papers, a success measurement refers to the evidence the authors provide to claim their proposed interaction techniques, models, devices, and systems to be "better than" or "comparable to" previous or other approaches. In empirical, methodological, theoretical, or survey papers, all the evaluation metrics were considered as the success measurements—we assumed that the authors considered the evaluation metrics essential for a successful solution to use them in the study. Because of this inherent difference between contribution types, we analysed them separately.

We first investigated the likelihood of success measurements being used to evaluate the solutions to each research challenge (Figure 4). We removed a challenge category for such an analysis if it consisted of fewer than five papers (i.e., a small sample size). We then performed additional analysis to offer insights tailored to the contribution types.

6.2.1 Artefacts. To address the issue of complexity in 3D interaction scenarios (27 papers), the artefact papers emphasised effectiveness (48% of the papers), efficiency (37%), experience (44%), and versatility (33%) to demonstrate the success of their solutions. That is, the proposed solution was often argued to achieve better performance, such as faster completion and fewer errors, provide more satisfactory user experiences, and be suitable for various application scenarios. Ergonomics (22%) and robustness (15%) measurements were less often used in the arguments, and there was little attention to realism, behaviour, and consistency measurements.

To address the challenge of the imprecise rendering of visual and haptic realism (seven papers), the dominant measurement was experience (71%), followed by effectiveness (43%), efficiency (43%), versatility (43%), and realism (43%). This indicated that while the solutions might have been proposed to improve realism, they could also enhance user experience (e.g., body ownership, sense of embodiment) and performance. The solutions were often demonstrated to remain functional in multiple applications.

Further analysis of all artefact papers suggested that when a solution achieved better performance (effectiveness or efficiency), the probability that it outperformed other solutions in the experience measurement was 76.9% and in the ergonomics measurement was 34.6%. If performance was improved, then the likelihood that the artefact performed superior in effectiveness and efficiency measurements was 34.6%. There were 24.4% of the solutions performed better in more or equal to four measurements.

6.2.2 Empirical, Methodological, Theoretical, and Survey. For the challenge of complexity in 3D interaction scenarios (seven papers), the selected papers employed similar measurements as in the artefact papers. More papers evaluated effectiveness (71%), efficiency (86%), ergonomics (43%), and experience (57%). Only one (14%) measured consistency in learning the techniques over time [159] and one conducted new studies on evaluating the robustness (14%) [182].

When exploring new interaction spaces and factors (27 papers), many papers focused on standard measurements such as effectiveness (67%), efficiency (63%), and experience (52%). Ergonomic measurements, including fatigue and workload, were also used in some cases (30%). Only a few papers assessed robustness (4%), versatility (7%), realism (4%), and consistency (4%) measurements. As for behaviour measurements (15%), there were explorations on whether the potential solutions could encourage positive user behaviours, such as decreasing the re-entry rate.

Similarly, more frequent measurements when comparing alternative solutions (15 papers) were effectiveness (60%), efficiency (93%), ergonomics (60%), and experience (73%). There were also limited analyses on versatility (7%), realism (13%), and behaviour (20%).

For developing evaluation methodologies (five papers), the papers mostly demonstrated that their framework or testbeds could achieve the desired purposes (effectiveness: 80%) and be adapted to new application scenarios (versatility: 60%). One empirical paper (20%) also considered efficiency, ergonomics, experience, and consistency effects when adjusting the evaluation methodology [187].

6.2.3 The Usage of Different Measurements over Time. Figure 5 summarised how success measurements were applied in different types of papers over the years. For artefact papers, more recent techniques were optimised to outperform baselines in a more diverse set of successful measurements (i.e., more colours in the stacked bars after 2016). Specifically, while versatility, effectiveness, efficiency, and experience seemed to be the initial focus, more recent techniques (after 2016)

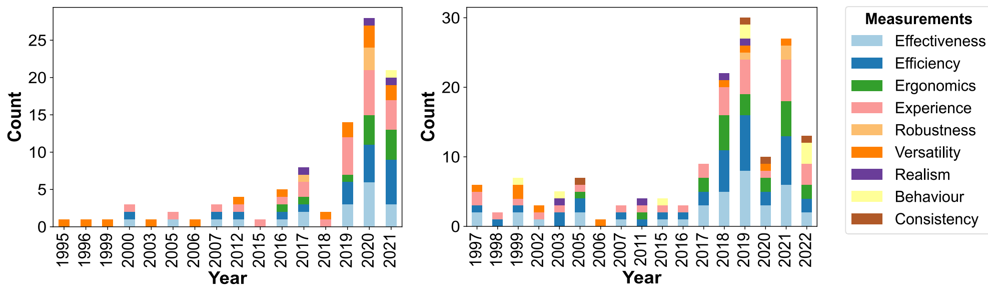

Fig. 5. Two stacked bar charts illustrating the utilisation of success measurements in artefact papers to substantiate the usefulness of proposed solutions (left), alongside the application of success measurements in empirical, methodological, theoretical, and survey papers (right).

concerned the improvement of ergonomics. They also started to improve upon measurements such as robustness and realism.

For empirical, methodological, theoretical, and survey papers, multiple measurements were employed to evaluate different perspectives of the solutions across years (i.e., the colours were more spread around). However, we noticed that measurements such as robustness, behaviour, and consistency were not as commonly used as performance measurements (effectiveness and efficiency), which could have given a more comprehensive picture of the usability of the technique.

7 Discussion

Based on our literature review, we first discuss findings on classic challenges and emerging trends in VR selection and manipulation, together with an overview of the solutions. We then evaluate whether current success measurements are suitable for these research challenges. We also present a framework based on Pareto Frontier [113] to optimise the techniques toward desired outcomes. We finally illustrate other potential issues from the literature that deserve attention in future work.

7.1 Classic Challenges and Emerging Trends

Upon categorising the research challenges publications aimed to solve, we see both classic challenges that have been actively investigated for decades and emerging trends that currently present a small number of papers but highlight important issues.

Classic research challenges were raised in the early days when there was little understanding of designing appropriate 3D user interfaces for selection and manipulation (Challenges 1–3). Researchers prototyped solutions to interact with objects in the surrounding 3D virtual space, explored new design spaces and features unique to 3D interaction, and compared alternative solutions for the best performance and interaction experience. With a more advanced understanding of the space, broad research challenges have been broken down into a multitude of specific sub-topics such as target occlusion [143, 163, 186], eyes-free acquisition [105, 177, 178, 190], multi-modality integration [81, 93, 144, 185], and virtual avatar-based interaction [29, 32]. We have detailed descriptions of these challenges and their solutions in Section 5.

There are also small but emerging topics in the field that are worth attention: coping with prolonged interaction and space limitations, rendering precise visual and haptic realism to reduce noticeable sensory mismatches, and integrating the selection and manipulation tasks into broad contexts and workflows (Challenges 4, 5, and 8). We expect further solutions of these research challenges. For example, with the rise of ergonomic issues, it seems that researchers have been putting more emphasis on designing for users themselves rather than on performance improvements. The topic could be further extended to consider accessibility issues, where users might have physical constraints with their bodies or environment-imposed situational disabilities (e.g., a person holding groceries might not be able to use their arms for other tasks) when interacting with VR systems [85, 110, 189]. We also envision the application of AI technologies and novel concepts to help systems better understand the environmental context and the user's needs and provide timely assistance [65, 121, 181] and more believable experiences [36, 158] during VR object selection and manipulation.

Two challenges investigated in the early days were revisited more recently. One is the challenge of underdeveloped evaluation methodology (Challenge 6). Though the existing evaluation framework is still helpful in ensuring internal validity (i.e., study rigour), experimental factors that could influence the study results (e.g., target size, distance, arrangement, density, occlusion, the presence of virtual avatar, background setting) are becoming too overwhelming to be fully crossed in a user study. It is thus difficult to determine to what extent the study results could be generalised to the intended applications and whether it is suitable to compare the results across studies [13]. We argue that it is still unclear how to address this challenge and will provide potential directions in Section 7.4.2. The other challenge is the limited support for collaborative object manipulation (Challenge 7). With the growing commercialisation of VR systems, it would be advantageous if users could complete tasks that require simultaneous manipulation of virtual contents with co-located or remote peers [47, 48, 125, 133, 169]. We expect to see more explorations considering the unique affordances of immersive VR headsets and the cooperation of multiple devices (e.g., VR headsets with AR glasses, tablets, and desktops) in object selection and manipulation.

7.2 Success Measurements

We raised three motivating questions when analysing the success measurements according to the research challenges. We here provide answers based on our analysis.

7.2.1 Has the Literature Over-emphasised Performance Measurements?. While improving performance regarding effectiveness and efficiency can be essential, it might not be desirable if achieved at the expense of increased cognitive load [5]. Moreover, users may prefer an interface that does not necessarily improve performance [120, 132]. These previous findings motivated us to explore whether VR selection and manipulation literature has been emphasised too much on performance measures. Our results (Figure 5) suggested that in more recent years, additional success measurements, such as user experience, ergonomics, and versatility, have been widely applied. Therefore, we point out that the existing publications do not over-emphasise performance.

7.2.2 Are the Existing Successful Measurements Good Enough?. According to our results, current measurements of artefacts and empirical studies centre mostly around effectiveness, efficiency, ergonomics, experience, and versatility. Effectiveness and efficiency capture objective performance measurements, while ergonomics and experience typically reflect subjective feelings. These are classic and reasonable measurements for user interface techniques in general [59].

Versatility demonstrates whether a solution can be applied to various applications or even enable new ones. This measurement could be especially useful for VR applications, given the diverse locations and forms of a target—a recent survey of VR consumer applications showed that targets can appear at varying distances relative to the user (e.g., on-body, within reach, and out-of-reach) and in different forms within the environment (e.g., 3D objects, UI elements, and moving avatars) [96]. Realism is another identified measurement, but one should consider whether it is appropriate before using it. Some use cases may benefit from beyond-real interaction techniques to enhance performance [1]. In contrast, other applications may aim to simulate how tasks are performed in real life, which may necessitate the use of realism measurements [96].

We further draw attention to three proposals. First, we argue that the success measurements related to robustness, consistency, and behaviour should be used more often. These measurements can provide a more comprehensive evaluation of the proposed solution. Specifically, they reflect a solution's adaptability across tasks with different difficulties (i.e., robustness) and interaction durations (i.e., consistency) and whether and how user behaviour will change because of the adaptation of the solution (i.e., behaviour). We encourage researchers to reflect on the following questions: (1) Robustness: Does the solution remain helpful in more extreme scenarios? (2) Consistency: Does the solution's usability increase or decay over time, either in the short term or in the long run? (3) Behaviour: How does the solution reshape user behaviour, and does it encourage positive behaviour?

Second, while current assessments of workload and fatigue are mainly based on questionnaires, we argue that objective metrics should be used more often. In our corpus, among the 32 papers where workload and fatigue were evaluated, only 5 used objective metrics. We encourage adopting objective metrics such as RULA scores [98, 109, 168] and Consumed Endurance [56], or even rough approximations such as hand movement distances or angles [44, 87, 183], along with questionnaires to estimate user workload and fatigue. Such objective measures could alleviate the potential experimenter effect when filling out a questionnaire. Additionally, recording limb and head movements should not be too cumbersome, given that hand and head tracking is often enabled in a headset-based VR system.

Third, we should re-think how to measure the success of an evaluation methodology. Researchers who proposed new testbeds or frameworks illustrated the usefulness of their approach through its effectiveness (e.g., through the demonstration of its usage) and versatility (e.g., reusable for new scenarios) [19, 20, 130] or showed that they were standard approaches for many previous papers [13]. However, there is a mismatch between these measurements and the goal (i.e., both internal and external validity) of a suitable method—researchers still have problems determining which methods (e.g., experimental tasks) they should choose to make their studies more "generalisable" to application scenarios. We illustrate our thoughts on resolving this problem in Section 7.4.2.

7.2.3 What Should We Expect about Future VR Selection and Manipulation Methods?. We believe that success measurements are the main determinants of shaping future selection and manipulation methods—they are treated as optimisation objectives of our endeavours. Therefore, the current prediction is that the future solution should perform reasonably well in the aforementioned success measurements (effectiveness, efficiency, ergonomics, experience, robustness, versatility, realism, behaviour, and consistency). However, we should also note that the successful measurements may correlate or conflict with each other. Our analysis has shown that performance measurements (effectiveness and efficiency) coupled with the experience measurement quite well; 76.9% of the proposed artefacts outperformed the baselines in experience measurement if they achieved better performance. In other cases, researchers and designers might need to decide the tradeoff between the measurements such as speed vs. accuracy tradeoff [126] and flexibility (versatility) vs. efficiency tradeoff [83]. Eventually, the future selection and manipulation method will have to pick a subset of success measurements to optimise while trading off other objectives.

Another related prediction is that there will be a clear separation between generalised solutions, which aim to handle numerous interaction scenarios, and specialised tools, which are dedicated to specific use cases [86, 178] (i.e., the breadth/depth dichotomy [58]). For example, the primary interaction metaphors based on Raycasting (or pointing in general) and virtual hand are unlikely to change significantly because of the significant commercialisation and their flexibility to be used in various interaction scenarios of selecting and manipulating properly sized, unoccluded menus, buttons, and objects. An implicit assistant from target prediction models can be applied

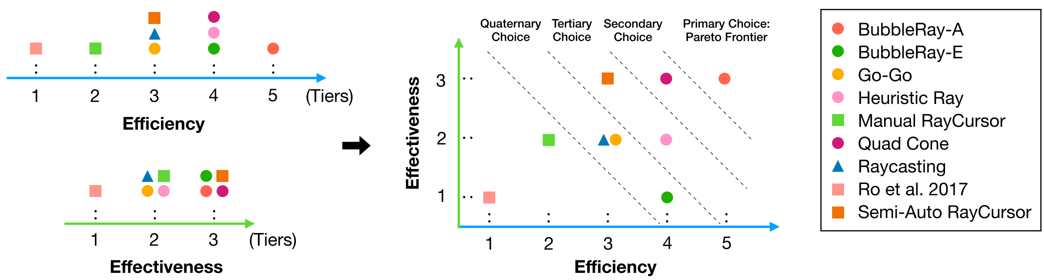

Fig. 6. To maximise performance measurements (i.e., efficiency and effectiveness), we placed all the candidate techniques onto a 2D plot with efficiency as the x-axis and effectiveness as the y-axis. We can compute the Pareto Frontier to determine the most optimal solution (i.e., *BubbleRay-A* in this case). The secondary, tertiary, and quaternary choices can also be concluded.

to enhance their usability when appropriate [54, 182]. More explicit enhancements such as visualisations and modalities [93, 145, 179], because of the added functionalities (and complexities), may continue proliferation to provide solutions for more specific scenarios such as for dense [9, 181], occluded [163, 186, 188], group-based [108, 155], and hands-free [85, 144] target selection and manipulation.

7.3 Advancing the Field with Multi-objective Optimisation

As discussed in the previous section, VR object selection and manipulation solutions may only optimise a subset of the success measurements most beneficial for the intended application, because tradeoffs can exist between different objectives. In this case, it is essential to determine which techniques are ideal and how to develop the most appropriate solutions for a given application. To achieve that, we build a framework based on Pareto Frontier [113] for deciding the most suitable technique(s) given multiple success measurements. Pareto Frontier contains a set of solutions that cannot be better off in any targeted objective without making it worse off in another objective. The main idea of our proposed framework is first to determine the desired success measurements for a given application and then choose the Pareto optimal solutions (i.e., Pareto Frontier) for the application. We illustrate the detailed process through an example.

Suppose we are looking for the best techniques for mid-range (around 1–5 meters) target selection. We want to maximise its performance measurements (i.e., efficiency and effectiveness). We pick two papers [9, 87] as our knowledge base for choosing the desired technique(s). In Lu et al.'s work [87], six techniques can be used for our purpose: *Go-Go*, *Raycasting* (i.e., *Naive Ray* in the paper), *Heuristic Ray*, *Quad Cone*, *BubbleRay-E*, and *BubbleRay-A*. From their comparison study, we can infer that for efficiency: *BubbleRay-A*>*BubbleRay-E*, *Heuristic Ray*, *Quad Cone*>*Go-Go*, *Raycasting*. For effectiveness: *BubbleRay-A*, *BubbleRay-E*, *Quad Cone*>*Go-Go*, *Heuristic Ray*, *Raycasting*. Similarly, we derive the following relationships based on the study in Baloup et al. [9]: For efficiency: *Raycasting*, *Semi-Auto RayCursor*>*Manual RayCursor*>*Ro et al. 2017*. For effectiveness: *Semi-Auto RayCursor*>*Manual RayCursor*, *Raycasting*>*Ro et al. 2017*.

Based on the above relationships, we can place the techniques from the two papers onto an efficiency and effectiveness scale by using the standard technique *Raycasting* as the anchor (see Figure 6, left). In both scales, the higher the tiers, the better the techniques perform on that scale. Note that we should be cautious about combining results from different papers, as the experimental environments differed. To demonstrate the optimisation framework, we assume these conclusions are generalisable (and we will discuss the generalisability issue in Section 7.4.2).

Since we want to optimise two objectives, we can place all the candidate techniques onto a 2D plot with efficiency as the x-axis and effectiveness as the y-axis (see Figure 6, middle). Following the definition of Pareto Frontier, where we identify the solution(s) that either of the dimensions could not be improved without worsening the other dimension, we conclude that *BubbleRay-A* should be our primary choice. A similar procedure can be followed to determine the secondary options (i.e., *Quad Cone*) by excluding the primary choices, as well as tertiary and quaternary options.

The demonstrated framework can be easily extended for future use cases. For example, we can consider higher dimensions with more optimisation objectives (e.g., four objectives including efficiency, effectiveness, experience, and robustness) if we have enough data support from previous empirical studies. Eyeballing the solutions might be difficult in higher dimensions, but the solutions can be computed programmatically. Furthermore, the optimisation objectives do not need to be restricted to the nine success measurements categorised in this research but with more precise separations (e.g., fun vs. perceived ease-of-use).

The framework can help practitioners decide which techniques to choose given a set of optimisation objectives and guide the future development of VR selection and manipulation solutions. The framework indicates that we should aim to develop solutions located at the Pareto Frontier of different combinations of objectives. It also suggests that we should conduct studies to verify the "tiers" of solutions, maybe with multiple studies to evaluate the generalisability of the conclusions in a given interaction scenario. In addition, we should try to compare a newly proposed solution to standard baselines (e.g., Virtual Hand or Raycasting) or the state-of-the-art to position it in the landscape of the techniques in the literature.

7.4 Additional Issues for Future Research

7.4.1 Proposal of Theories that Can Explain. Recent discussions in HCI, in general, have been putting a lot of attention on theory building (e.g., References [60, 84, 117, 118]). A recent survey on VR selection and manipulation by Bergström et al. also highlighted the importance of evidence accumulation for theory building [13]. However, the papers deemed to have theoretical contributions (as categorised in our work) concentrated on design spaces or frameworks [175]. While we have seen a few papers on empirical models that can predict user selection behaviour [182] or intended target of interest [54], these models are mainly descriptive. They do not provide a sense of understanding about the causes of the predicted event. Since being able to explain the causal mechanism is indispensable for a scientific theory [134], we should aim to build theories that can provide understanding regarding the underlying cognitive and motor mechanisms of VR object selection and manipulation. This may require, for example, studying the underlying control processes of an interaction technique [112].

7.4.2 Study Methodology and Generalisability. Good generalisability allows research findings to remain valid across relevant application scenarios. One issue we have identified was the mismatch between the success measurements and the goal of evaluation methodologies. Measuring generalisability is difficult without numerous studies on the relevant topics. So, how can we determine whether a methodology is valid when first proposed? Specifically, should we choose to use the classic layout based on 2D Fitts's Ring [150] or the randomised distribution of the objects in 3D? Should we use a colourful background to get users engaged in the experiment [187] or use a monochrome VR environment to minimise distractions? We believe these choices all matter with the balance between concreteness and abstraction when constructing an evaluation methodology.

The tools are typically designed for completing a (set of) concrete interaction task(s). If the study methodology closely mimics how users complete the designated interaction tasks, then we should have more confidence in saying that the study results are generalisable in these tasks. To closely approximate the concrete tasks, the methodology may leverage similar object distributions (e.g., following specific layouts) and create the feeling users typically have when completing such tasks (e.g., engaged). In contrast, the study methodology may extract only high-level features in the concrete interaction tasks, because it aims to address numerous of them, making the design more abstract (e.g., Fitts's Ring). It is more difficult to tell whether the results produced in the abstract task settings are generalisable to concrete scenarios because of the simplifications. The key to capturing generalisability with a suitable study methodology is to balance concreteness and abstraction if there are multiple intended interaction scenarios. Note that both concrete and abstract methods could achieve internal validity but may have different implications for external validity.

Existing literature demonstrates a few examples of how study findings can be more confidently generalised to intended applications: (1) by emphasising a specific application scenario and only evaluating that scenario [155, 161, 165]; (2) by experimenting with both abstract and concrete example applications [164, 184]; (3) by testing the study results in wide parameter ranges, especially in more challenging conditions [87, 182]. In addition, to ensure the generalisability of the results, we concur with Bergström et al. [13] that we should also regularly perform longitudinal, outside-of-lab studies. It can also be useful to perform a meta-analysis that compares different techniques in terms of their performance (e.g., effectiveness and efficiency). However, each research paper typically employs different methodologies and task settings, making direct comparisons and analyses challenging. One interesting future direction to enable this without running numerous user experiments is to simulate users with an AI agent [62].

7.4.3 Measuring Accessibility. In addition to the nine success measurements discussed in the existing literature, it would be helpful to add the measurement of accessibility. Many people suffer from disability worldwide [110, 115]. Furthermore, every user could experience situational impairments, depending on their situations, contexts, and environments (e.g., a user may not be able to use their arms for interaction while lifting heavy goods) [139, 142, 174]. It is thus useful to consider how proposed methods can be adapted to support people with (situational) disabilities such as visual [189] or motor [111] impairments to accomplish selection and manipulation tasks. It may also be interesting to develop standard tools for evaluating the accessibility of an interaction technique.

7.4.4 Usability Measurements during Practice. One aspect often overlooked in the existing literature is the usability measurements of solutions while users are still practising how to use them (i.e., at the start of the learning process). Previous research typically removed data in the practice trials from the formal experimental data or gave participants enough time to get familiar with the proposed methods [61, 140, 182, 186]. However, it can be helpful to quantify the usability of the solutions during the early learning process, which can provide valuable information on whether users can quickly adapt to these solutions. For example, a recent study demonstrates how to evaluate motor learning when adapting to new interaction techniques [180].

7.5 Summary of Recommendations

We summarise the main takeaways from our discussions in the following:

- Classic challenges remain attractive for future research, including complexity in 3D interaction scenarios, underexplored interaction spaces and factors, and unknown comparative usability of the candidate solutions. Meanwhile, we should also pay attention to the emerging trends, where researchers have been proposing solutions to cope with the limitations in a user's physical space, render believable visuals and haptics when appropriate, integrate the techniques to a broader context and workflow, develop better evaluation methodology, and enable collaborative object manipulation.

— While the existing literature has employed a multitude of success measurements to evaluate the candidate solutions, researchers should further consider (1) assessing the robustness, consistency, and behaviour aspects more often, (2) using objective metrics to accompany the current questionnaire-based measurement of workload and fatigue, (3) re-thinking how to evaluate the success of a new evaluation methodology.
— The optimisation framework introduced in Section 7.3 can help choose an appropriate solution for a given scenario with specific design objectives. Furthermore, the framework can be used as a guide to developing future VR selection and manipulation solutions. Notably, we should aim to propose techniques to be in the Pareto Frontier of different design objectives, verify the comparative performance of the alternative techniques on various objectives, and compare a newly proposed solution to standard baselines and the state-of-the-art.
— There should be more focus on (1) proposing theories to explain, for example, why specific interaction techniques improve usability, (2) ensuring the generalisability of the study conclusions by, for example, striking a balance between the concreteness and abstraction of an experimental task, (3) considering measuring the accessibility of a candidate solution, and (4) performing usability measurements when users are practising a new solution.

7.6 Limitations

7.6.1 Completeness. We employed systematic query searches and key literature identifications to build our corpus, making us confident in including most relevant papers. However, we acknowledge that we could inadvertently miss some. In other words, this corpus cannot be treated as an exhaustive and complete list of VR object selection and manipulation research. We highlight that our goal was to identify key challenges, solutions, and success measurements in the domain, and the current corpus serves as a representative subset of the most relevant papers. We aim to address this inherent limitation of a systematic review by making our dataset and search queries transparent and open-source for future research to iterate and expand upon.

7.6.2 Reality–virtuality Continuum. This research only included relevant research built with VR headsets but not other VR or AR displays. Our rationale was based on Bowman et al.'s research [17, 89] comparing multiple interaction techniques under different displays (i.e., CAVEs and HMDs). They found that migration of techniques to other displays could sometimes work but could also cause serious usability problems due to the different display properties. It was thus difficult for us to justify whether solutions that worked on other displays could also be transferable to VR headsets. Therefore, we restricted our scope to VR headsets for simplicity. However, we want to highlight that solutions proposed in other VR or AR displays (e.g., CAVE, AR glasses, volumetric displays) may also be applicable and adaptable for VR headsets [74, 104].

8 Conclusions

In this work, we have presented a survey on object selection and manipulation in VR headsets. We illustrated eight research challenges in the field with the corresponding state-of-the-art. In addition to the classic challenges, such as complexity in 3D interaction scenarios, we also identified emerging trends in ergonomics issues, visual and haptic renderings, evaluation methodology, collaborative manipulation, and context integration. Furthermore, we evaluated how existing publications measure the success of their contributions and derived nine measurements of success (i.e., effectiveness, efficiency, ergonomics, experience, robustness, versatility, realism, behaviour, and consistency). We reflected on current practices regarding whether the publications over-emphasising performance measurements and whether the existing measurements are appropriate to solve the research challenges. We also envisioned the future VR selection and manipulation methods and offered an optimisation framework for developing or comparing new solutions for intended applications. In addition, we considered future research directions such as explainable theories, research findings generalisability, and technique accessibility. Our work can benefit researchers in the field to gain new perspectives on the future advancement of VR object selection and manipulation.

Appendix

A Geographical Distribution Analysis

Figure 7 shows the geographic distribution of authors involved in the reviewed papers. The final counts consider the corresponding country of the authors' institution, and we ensured that a paper with several authors from the same country is counted only once. The results indicate that the majority of publications in this domain have originated from countries in North America, Asia, Europe, as well as Australia.

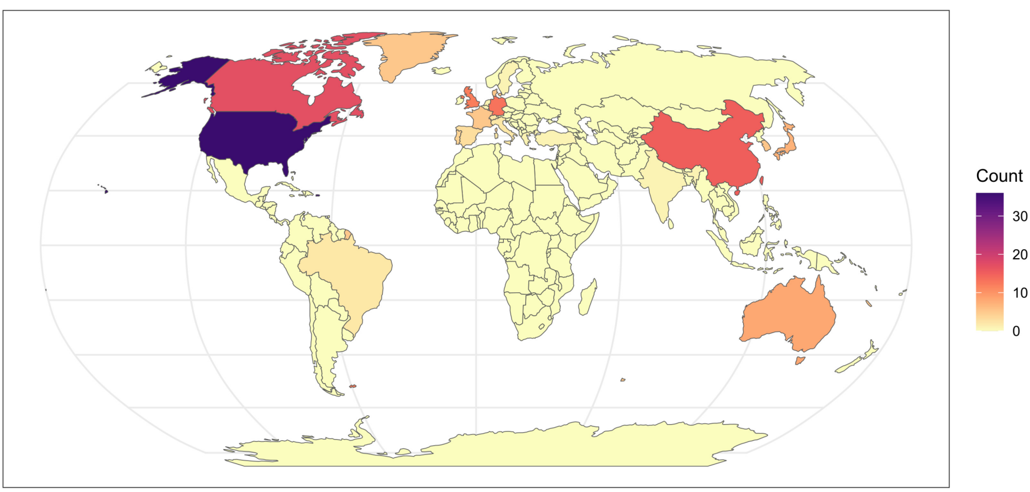

Fig. 7. The geographical distribution of the authors who have contributed to the published papers.

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