Interactive mixed reality widgets for precise dexterity of tool manipulation to enhance surgical procedures in Industry 4.0 realm

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DELL'INGEGNERIA INDUSTRIALE

Final Dissertation

Interactive Mixed Reality Widgets for Precise Dexterity of Tool Manipulation to Enhance Surgical Procedures in Industry 4.0 Realm

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by
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Abstract

Complex medical procedures, particularly those involving surgery, demand exceptional precision in spatial 6DOF (Six Degrees of Freedom) tool manipulation, where even minor errors can result in irreversible damage or undesirable outcomes. In this context, precise tool alignment is crucial, whether in minimally invasive surgeries or delicate procedures such as dental implantology. Mixed Reality (MR) technology has emerged as a promising tool for addressing these challenges by providing surgeons with real-time, spatially accurate guidance through visual assets known as widgets. These MR widgets have the potential to support surgeons by superimposing helpful information directly onto the physical environment, enabling them to perform complex tasks with higher precision. However, despite the advancements in MR technology, current approaches remain predominantly static or quasi-static, leading to persistent errors due to a lack of adaptive and dynamic solutions. Additionally, the absence of standardized guidelines for widget design and the underemphasis of user interface (UI) considerations in MR systems exacerbate usability issues, leading to increased cognitive and physical task loads for surgeons and ultimately detracting from performance and outcomes.

This thesis addresses these challenges through a systematic investigation that employs experimental methodologies, including user studies with surgeons and domain experts, to evaluate and optimize innovative MR-based solutions. A comprehensive literature review reveals significant gaps in existing MR systems, such as inadequate widget design, suboptimal usability, high cognitive task demands, and limited adaptability in real-time surgical contexts, particularly in dentistry. A key contribution of this work is advancing the understanding of user-centered UI design for precision tool-to-target guidance systems. This research highlights the importance of addressing persistent challenges such as visual clutter, occlusion, and inclusivity, ensuring that widgets cater to diverse user needs, including those with visual impairments or varying cognitive capabilities.

Building on these insights, this thesis introduces interactive widgets that integrate principles of cognitive perception, particularly those derived from Gestalt theory. By applying Gestalt principles such as proximity, continuity, and figure-ground organization, the research focuses on optimizing visual design and incorporating real-time error feedback mechanisms that respond to user actions. The result is a set of interactive widgets that significantly enhance the positional and angular precision of the tools while managing cognitive load and task completion time effectively.

The findings demonstrate that the proposed widgets outperform traditional, static designs in terms of precision, efficiency, and usability. These widgets improve tool manipulation accuracy, streamline cognitive processes involved in high-stakes procedures, reduce task completion times, and enhance user preference. Moreover, these designs' modular and adaptable nature extends beyond medical applications, offering valuable solutions for industries requiring high precision and safety, such as manufacturing, maintenance, and assembly.

Furthermore, this research presents a flexible, open-source evaluation framework for MR widget design, promoting standardized testing methodologies and fostering greater collaboration within the scientific community. This framework facilitates consistent development and assessment of MR systems, ensuring reliability and cross-domain applicability.

Looking to the future, this research explores several directions for enhancing MR widget design, including integrating haptic and auditory feedback systems to increase interaction fidelity, developing adaptive and personalized user interfaces tailored to individual user needs, and establishing standardized design guidelines to encourage innovation and consistency across industries. The aim is to pave the way for safer, more efficient, and precise outcomes in MR-assisted procedures and systems, providing a foundation for continued advancements in MR-based precision tools.

Keywords: Precision, surgical tool manipulation, widgets, dexterity, UI design, mixed reality.

Hayatta en hakiki mürşit ilimdir.
The truest guide in life is science.
M. K. Atatürk

Contents

Part 1: Thesis Overview

This thesis is submitted in partial fulfillment of the requirements for the degree of *Philosophiae Doctor* in Industry 4.0 at the *Politecnico di Bari*, the area of Innovation. The research was conducted under the auspices of the *Virtual Reality and Reality Construction Group, VR*^{3}*Group* at the Politecnico di Bari, with the invaluable guidance of Professor **Michele Fiorentino**, between 1 January 2022 and 31 December 2024. It represents a culmination of my academic and professional dedication to advancing precision guidance using Mixed Reality technologies, with a particular focus on their applications in medical and industrial settings.

During my doctoral journey, I spent six months conducting research at the Technical University of Munich, Germany, between 1 May 2023 and 30 November 2023 under the supervision of Professors **Ulrich Eck** and **Nassir Navab**. This experience was pivotal, allowing me to collaborate with leading medical experts from LMU Hospital, Department of Operative Dentistry and Periodontology (Munich, Germany), exchange ideas in an interdisciplinary environment, and enrich my work with diverse perspectives and methodologies. The time spent abroad enhanced the technical depth of this thesis and broadened my academic horizon, inspiring new approaches to tackling the challenges posed by precision tasks in Mixed Reality environments.

Furthermore, I spent six months conducting collaborative research at the Polyclinic University Hospital of Bari, Italy, within the Department of Ophthalmology. During this period, I worked closely with Dr. **Giancarlo Sborgia** and his team on implementing VR mobility assessment technology for patients with visual impairments. This research focused on utilizing virtual reality to evaluate and improve patient mobility, offering valuable insights into how immersive technologies can be integrated into their diagnostics and rehabilitation. The experience greatly enhanced the practical application of my research, bridging the gap between technological advancements and real-world healthcare solutions.

Designed for a broad audience, this thesis aims to bridge the gap between advanced technology and practical application, focusing on delivering safer, more efficient, and more intuitive systems for precision tool manipulation tasks. This work aspires to contribute meaningfully to the ongoing evolution of Mixed Reality technologies and their transformative potential across medicine, industry, and beyond. During my PhD, I foster collaboration and inspire further advancements by making the designs, results, and frameworks open-source.

This chapter outlines the structure and dissemination of the PhD research outcome conducted during the three years. It highlights the alignment of individual chapters with published works, presents the broader outcomes of the research, and emphasizes the practical implications and contributions to the academic community, industry, and society at large. A full list of the publications and a discussion of the open-source tools and supplemental materials shared to foster ongoing innovation and collaboration are provided.

Structure of the Thesis This thesis has five main parts with eight chapters, and the arrangement of each chapter presents the chronological order of the research done during the doctoral study.

- ***Part 1*: Thesis Overview Chapter 0** presents the research path, structure of the thesis, industry, and research contributions and publications overview.
- ***Part 2*: Introduction Chapter 1** presents the main motivation of the thesis that provides a comprehensive background and contextualizes the research by relating individual chapters to each other and articulates the motivation for pursuing innovative solutions for tool manipulation in precision tasks, particularly within medical and industrial applications.
- ***Part 3*: Systematic Review Chapter 2**, **Chapter 3** discusses the foundational framework and methodologies developed for this research as a systematic review for understanding the existing literature concepts.

- ***Part 4*: Methodology** **Chapter 4**, **Chapter 5**, and **Chapter 6** focus on specific interactive widget designs inspired by the perception theory of Gestalt and their experimental validation. **Chapter 6** extends these findings to new user studies with experts in dental implantology. This chapter is the outcome of my abroad experience at the Technical University of Munich.
- ***Part 5*: Thesis Conclusion** **Chapter 7**, and **Chapter 8**, the conclusion synthesizes the main outcomes and discusses future directions for extending the research into broader domains, emphasizing its scalability and adaptability to various applications.

Relevance to Industry and Society This research contributes to advancing precision guidance technology, with far-reaching implications for industry and the general population. In the medical field, the improved accuracy and usability of these widgets have the potential to enhance surgical outcomes, reduce errors, and improve patient safety. These tools can optimize assembly, welding, and maintenance processes in industrial applications, contributing to greater efficiency and reduced operational costs.

Moreover, the accessibility of these widgets ensures that their benefits extend to a broader audience, fostering inclusivity and addressing the needs of diverse user groups, including individuals with visual or physical impairments. The open-source nature of this work not only accelerates adoption in professional settings but serves as a foundation for educational purposes, enabling students and researchers to engage with cutting-edge technology and further innovate in this domain.

Publications and Community Contributions This thesis builds on the insights gained from numerous peer-reviewed publications, of which I am the primary author. These contributions highlight the iterative nature of the research process and underscore my commitment to advancing the state of knowledge in this field. While this document represents the culmination of my doctoral studies, it also serves as a starting point for future exploration and innovation.

The papers are preceded by an introductory **Chapter 1** that relates them to each other and provides background information and motivation for the work [7], [6], part of this chapter presented at the leading conference International Symposium on Mixed and Augmented Reality (ISMAR) 22 as doctoral consortium.

A version of **Chapter 2**, has been presented also in ISMAR 24 as journal [2] while **Chapter 4** and **Chapter 3**, **Chapter 5** have been presented in International conferences ISMAR22 and ADM23 [9], [8]. **Chapter 6** has also been presented in the ISMAR 2024 as journal [3].

Various peer-reviewed publications, conference presentations, and collaborative projects reflect my contributions to the field. Beyond the core chapters of the thesis, I co-authored research exploring MR applications in retail and user interface design, further broadening the scope of the work [4], [5], [1].

By sharing this work with the global community, this Ph.D. aims to empower researchers and practitioners to reimagine precision guidance systems, fostering interdisciplinary collaboration and unlocking new possibilities for safer, more efficient, and more inclusive technological solutions.

This thesis research has yielded significant outcomes, both in terms of academic insights and practical tools. The innovative tool manipulation widgets developed during this Ph.D. are versatile and designed to improve precision and usability in high-stakes environments such as surgery, manufacturing, and assembly. These widgets address critical challenges such as cognitive load, spatial precision, and inclusivity, setting new benchmarks for user-centered design in Mixed Reality applications.

To maximize the impact of this work, the widgets and their associated designs are made available as open-source software. This open-access approach ensures that researchers, developers, and industry professionals can easily implement and adapt these tools to their needs. The open-source repository promotes transparency, collaboration, and innovation within the research community. The supplementary materials include additional resources to support developers in implementing and testing the widgets:

- Open code source [1]: Fully documented code for implementing the dynamic widgets, allowing for quick integration and adaptation to new use cases.
- Quantitative Results: Detailed datasets and statistical analyses from user studies, providing benchmarks for future evaluations.
- Video Presentations [2]: Demonstrating the widget functionalities in real-world scenarios to aid understanding and application.

The full list of papers written by the author is reported hereafter.

International Journal Articles

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[1] Dynamic widget open source link: https://github.com/Vr3xMelab/DW

[2] Dynamic widget video presentation: https://youtu.be/QTOl9vA7TcA?feature=shared, TOTTA presentation: https://youtu.be/jwWq1F_6xA0?feature=shared

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I wish to thank my colleagues at the Virtual Reality and Reality Reconstruction Group (VR^{3}Group). Your collaboration and support have made this academic journey both enriching and enjoyable.

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Thank you all.

Part 2: Introduction

Chapter 1

Motivation of the Thesis Research

1.1 Problem

In various high-stakes domains, such as surgery, manufacturing, and industrial applications, aligning tools with targets in three-dimensional space is a critical task that demands high precision. This process, referred to as Tool-to-Target (TOTTA) manipulation, involves spatial manipulation along six degrees of freedom (DoF)—three translational (x, y, z) and three rotational (pitch, yaw, roll)—to position a tool accurately relative to a target [1]. TOTTA tasks are central to procedures that require extreme precision, such as inserting a surgical instrument into a specific anatomical location, positioning diagnostic sensors on curved surfaces, or guiding welding tools along a seam. While conceptually straightforward, achieving the required accuracy is complex and cognitively demanding.

This thesis aims to develop interactive spatial widgets to improve tool manipulation dexterity in next-generation AR/VR/MR technology without hardware limitations. Mixed Reality (MR) has emerged as a promising solution for aiding users in performing TOTTA tasks, particularly by overlaying real-time digital feedback on the physical environment. We call this overlaying information as MR tool manipulation widgets. MR widgets offer the potential to improve task performance by providing spatial guidance that supports users in achieving precise tool alignment. However, despite the growing interest and application of MR widgets in TOTTA tasks, the design of MR widgets specifically tailored for these tasks remains underexplored. Current MR-based systems often rely on static or semi-static visual elements that fail to adapt to the dynamic nature of TOTTA tasks, leading to reduced effectiveness and increased cognitive load for users.

The Gestalt theory of perception [2] provides valuable insights into how users perceive and interpret visual information, which is critical for designing effective MR interfaces. According to Gestalt principles, the human brain tends to group objects that are close to each other (proximity), follow continuous patterns (continuity), and distinguish between a focal object (figure) and its background (ground). These principles can be applied to designing visual guidance widgets in MR systems to improve user performance by enhancing the guidance's clarity, intuitiveness, and responsiveness.

In designing MR widgets, the effective application of Gestalt principles can significantly improve how users perceive spatial relationships and align tools with targets. For instance, the principle of proximity suggests that visual elements that are closely aligned should be perceived as related, making it easier for users to assess alignment in real time. Similarly, the figure-ground organization principle can ensure that the tool and target stand out clearly from the background, reducing visual clutter and focusing the user's attention on the most relevant elements. These perceptual insights can be leveraged to design MR widgets that provide clearer, more intuitive spatial feedback.

In dental implantology, for example, MR can provide real-time guidance on drill tool manipulation, helping to avoid critical anatomical structures such as nerves and sinuses [3], [4]. The goal is to guide the drill in 3D space with high accuracy—typically within tolerances of less than 1 mm and a few degrees of angular deviation—while avoiding vital anatomical structures such as nerves, sinuses, and adjacent teeth [5], [6]. This task must be carried out in a confined, partially visible, and constantly changing environment: the patient's oral cavity. Factors such as soft tissue movement, bodily fluids, patient discomfort, awkward drill angles, and suboptimal lighting make this procedure physically and mentally demanding [7], [8].

To address these challenges, several technological solutions have been proposed. Custom-made 3D-printed surgical templates offer physical guidance but are expensive, require lab preparation, and lack intraoperative flexibility [9]. More recently, screen-based navigation systems have emerged, using preoperative data and real-time tracking to guide the dentist via a 2D monitor. However, these systems introduce divided attention, as the clinician must look away from the patient to view guidance on a separate display and then mentally map 2D screen feedback to 3D hand movements [10], [11]. This process increases cognitive load and reduces procedural efficiency.

Mixed Reality (MR) enables the overlay of 3D visual guidance directly onto the patient's anatomy, allowing the dentist to view and act within the same space. MR enables in-situ visualization, keeping the clinician's focus on the surgical field and potentially improving alignment accuracy [12], [13]. Despite their potential, current MR widgets often suffer from static visual cues and a lack of real-time interactivity, which limits their effectiveness [14], [15]. Studies vary in methodology, metrics, and realism of testing environments. Few involve real practitioners; even fewer include co-design or feedback loops in their development. Additionally, these systems do not always account for the cognitive demands placed on clinicians, who must balance the visual cues with physical actions in a confined, dynamic environment [16], [17]. This issue highlights the need for dynamic MR widgets that improve spatial alignment and reduce cognitive load by adhering to perceptual principles like Gestalt proximity and continuity.

1.2 Objectives

The core objective of this research is to develop and evaluate MR widgets specifically designed for TOTTA tasks, with a particular focus on dental implantology as a case study. By applying established perceptual theories, such as the Gestalt principles, the thesis aims to create visual guidance systems that adapt to the user's movements, provide continuous feedback, and improve the precision of tool manipulation in constrained environments. Through this approach, the research addresses the technical, cognitive, and usability challenges inherent in high-precision tasks, aiming to enhance the overall user experience and task efficiency.

The following research objectives guide the direction of this work:

1. Identify Gaps in Widget Standardization In **Chapter 2**, and **Chapter 3**, a systematic literature review is conducted to map the landscape of visual widget use in MR-based TOTTA tasks.

- The absence of standardized design guidelines for tool-to-target widgets;
- The fragmented and inconsistent approaches to widget visualization;
- The minimal involvement of end users in the design, iteration, or validation phases.
- Revealing key limitations in the current state of the art MR widgets design in dentistry

This review synthesizes findings across domains to uncover promising patterns and overlooked issues, helping to inform better widget design practices.

2. Implementation of Novel Widgets The second objective involves the design and implementation of interactive widget systems, evaluated primarily in the context of dental surgery but with broader applicability to other domains requiring precision tool manipulation.

Chapter 4, **Chapter 5**, and **Chapter 6** explore three different widget designs, each tackling specific challenges in MR interface development.

Visual Clutter and Occlusion

Visual widgets are integrated into the surgical field of view, where improper design can result in occlusion, clutter, and loss of situational awareness. This research examines how spatial arrangement, transparency, shape, and motion can be optimized to:

- Maintain visibility of critical elements in dynamic 3D scenes;
- Supports accurate depth perception and visual hierarchy;
- Avoid overwhelming the user with excessive or overlapping information.

Gestalt perceptual principles — proximity, continuity, and figure-ground separation — guide widget layout and behavior. Additionally, collimation is applied to align widget elements with the user's natural viewpoint, further enhancing spatial comprehension in real-time interactions.

Precise Tool Manipulation

Widget designs are evaluated for their ability to reduce positional and angular errors in surgical drill alignment. This includes:

- Designing intuitive, dynamic interfaces that reflect spatial deviation;
- Providing real-time feedback to support fine-tuned tool movement;
- Investigating how interface geometry and behavior influence accuracy.

The core research question—"How can widgets help improve user performance in tool-to-target tasks?"—drives the development of design strategies that leverage human perceptual strengths to improve precision, especially in high-stakes, constrained workspaces.

Task Load and Cognitive Effort

A critical objective is assessing how different MR widgets affect task load, including cognitive and physical dimensions. This includes:

- Measuring user-reported and performance-based indicators of mental effort;
- Identifying design features that contribute to overload or confusion;
- Optimizing feedback and layout to reduce complexity and learning curve.

While many MR widgets focus on hardware improvements, this research emphasizes the qualitative experience of the user, exploring how interface simplicity and clarity can streamline workflows and enhance performance.

Integrate Co-Design This thesis highlights the importance of developing end-user-oriented interfaces. Rather than designing for generic use cases, the goal is to create widgets that meet the specific needs of clinicians, engineers, and domain experts.

Chapter 6, the co-design methodology is applied through:

- Focus groups with practicing dentists and surgeons;
- Iterative testing with real dentist users and refinement based on user input.
- Optimizing feedback and layout to reduce complexity and learning curve.

This user-centered approach ensures that the final widget designs are grounded in real workflows and constraints, leading to higher usability, lower task load, and better acceptance in real-world environments. This research challenges traditional top-down interface development by involving end-user dental experts throughout the process and supports creating precise MR widgets.

In line with these goals, the thesis emphasizes a user-centered development process incorporating co-design methodologies, ensuring dental professionals actively design and evaluate the MR widgets. By doing so, the research aims to create MR solutions that are technically effective but also practical and user-friendly, ensuring their applicability in real-world clinical settings. The findings from this research will contribute to advancing MR interface design, providing valuable insights and validated interface guidelines for future development in medical and industrial domains.

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Part 3: Systematic Review

Widgets in literature

While previous **Chapter 1**, introduced the motivation and research objectives for this thesis, focusing on the need for precision in medical and industrial procedures, particularly in dentistry, this part, builds upon the foundational background of the literature.

Specifically, a systematic review was presented of current methods used for tool-to-target positioning in spatial augmented environments, identifying critical gaps in widget design, usability, and standardization. This part provides an overview of the importance and approach of conducting a systematic review of Tool to Target (TOTTA) manipulation widgets in general Mixed Reality (MR) systems, and how the insights derived from this broader analysis directly impacted the development of the specific state-of-the-art review and experimental methodologies applied to dental drill tool manipulation in MR systems. The systematic review of TOTTA widgets explored the existing designs, evaluation methods, and underlying principles, providing a comprehensive understanding of the current landscape. Based on the findings of this review, a tailored experimental framework was developed for evaluating and designing MR drill tool manipulation widgets for dental applications. This chapter highlights the value of literature-driven methodologies, the design considerations based on the analysis, and the key steps taken to ensure the experiments aligned with established principles and specific domain needs.

Understanding the current state-of-the-art is important in developing novel methods of MR widgets. No unified approach or comprehensive study existed in the case of TOTTA widgets in MR environments. While MR technology has shown immense promise in improving the precision of tool manipulation in various domains, including surgery, engineering, and industrial applications, the specific design of interactive visual widgets to guide TOTTA remains a fragmented field. Many different design approaches and evaluation methods have been proposed, each with strengths and limitations.

A systematic review of TOTTA widgets was essential to identify trends in design patterns, feedback methods, and interaction styles. By analyzing and comparing the results of various approaches across various domains, we gained valuable insights into which design elements were consistently effective, which were domain-specific, and which were not adequately tested. This review clarified the broader landscape of TOTTA widget development and identified gaps in the literature that could be filled through innovative design contributions in future research.

This systematic review serves two key purposes:

Chapter 2 To synthesize the broad spectrum of research and highlight best practices in TOTTA widget design.

Chapter 3 To lay the groundwork for the subsequent domain-specific study of dental tool manipulation in MR, ensuring that the experimental design and methodology are grounded in the field's most up-to-date and comprehensive understanding.

The insights drawn from the general review of TOTTA widgets directly informed the state-of-the-art analysis of dental drill tool manipulation in MR. By identifying the most commonly used visual designs, interaction methods, and evaluation criteria in the broader field of TOTTA widgets, we could tailor these findings to the specific needs and challenges of dental surgery scenarios.

Several key lessons from the general review had a direct influence on the design of the dental-specific MR widget:

Widget Design: The systematic review revealed that certain widget types—such as Box, 3D Axes, and 3D Models—were more widely used across domains. These designs were adapted to the dental context by considering how to ensure precision in the unique, constrained environment of the mouth, where limited space and high precision are crucial.

Feedback Mechanisms: The review showed that effective feedback is integral to user performance, whether visual, auditory, or haptic. For dental procedures, where tool alignment and positioning are critical, the review's findings on dynamic feedback led to the inclusion of real-time positional and angular corrections within the dental widget design.

Evaluation Methods: The review highlighted the variations in testing methodologies, participant demographics, and performance metrics. This insight guided the experimental setup for the dental widget studies, ensuring that we addressed these gaps by establishing standardized evaluation protocols that incorporate factors like cognitive load, user comfort, and task precision in the dental setting.

Using the findings from the systematic review, we ensured that the dental widget design was informed by a robust understanding of the successes and limitations of existing designs across diverse domains while also addressing the needs of dental surgeons.

The systematic review also shaped the experimental framework employed in the subsequent chapters. Understanding the common limitations of previous studies, particularly the lack of consistency in experimental setups, biases related to participant selection, and the absence of comprehensive evaluation metrics, we developed a more rigorous methodology for testing MR dental drill manipulation widgets.

Key aspects of the experiment design include:

Standardized Setup: Following the recommendations from the review, we established a consistent and replicable experimental setup, ensuring that all variables—such as tool sizes, target positions, and feedback methods—were controlled across trials.

Participant Demographics: The review revealed biases in participant demographics, such as the predominance of right-handed, young male participants. To mitigate this, our study includes a more diverse sample, considering gender, handedness, and professional backgrounds (e.g., dental students and practicing dentists).

Performance Metrics: The review's focus on task completion time, positional and angular errors, and subjective user experiences (e.g., perceived comfort, cognitive load) led to the adoption of a similar set of metrics in our dental experiments, ensuring that the widget's effectiveness could be measured in multiple dimensions.

Evaluation Criteria: Based on the findings from the review, the experiments will incorporate both quantitative and qualitative measures, ensuring a balanced approach to understanding user performance and experience with the MR widgets.

Therefore, the following chapters underscore the critical importance of systematic reviews in guiding the design and methodology of research in emerging technologies. By thoroughly analyzing the existing literature on TOTTA widgets in MR environments, we were able to inform the development of a dental-specific MR tool manipulation system grounded in well-established design principles and tailored to address the unique challenges of dental surgery. The findings and methodologies discussed in this chapter provide a clear foundation for the subsequent research, where novel MR techniques for dental drill manipulation will be explored and evaluated. Through this structured, literature-driven approach, we ensure that the next steps in MR dental surgery innovations are built upon a solid understanding of what has already been achieved and what remains to be addressed.

Chapter 2

Precise Tool to Target (TOTTA) Manipulation Widgets in Spatial Environments

Chapter Summary

This chapter lays the groundwork for understanding the challenges in the general field before entering the dentistry field state of the art and provides a comprehensive context for the novel contributions presented in the following chapters. This chapter addresses the general Tool to Target (TOTTA) manipulation problem, which involves the spatial position and rotation guidance of a real or virtual tool (TO) towards a real or virtual target (TA), a crucial task in MR applications. Errors in this task can have severe implications for safety, performance, and quality, particularly in fields such as surgical implantology and industrial maintenance. Despite its importance, the TOTTA problem has not been studied in-depth, and relevant research is scattered across different domains with isolated design approaches.

The chapter presents a systematic review of TOTTA visual widgets, examining 70 unique designs from 24 papers. The review reveals that the primary method for guiding the tool toward the target in TOTTA applications is visual overlap, also known as "collimation" feedback. This intuitive, pre-attentive feedback is provided by simple, geometric widgets, such as boxes, 3D axes, 3D models, 2D crosshairs, globes, tetrahedrons, lines, and planes. These widgets often represent both the tool and the target using the same shapes, distinguishing them by topological elements like edges, vertices, faces, colors, transparency levels, and additional shapes, widget quantities, and sizes. The review also highlights the lack of established standards in the field, particularly regarding testing procedures. Current testing methods are limited and often use partial sets with inconsistent setups, making comparisons difficult. Moreover, the research uncovered a participant bias in existing studies, with a predominance of right-handed, young male participants who were not color-impaired.

Contents

2.1 Sytematic Review Methodology

The research questions that motivate the literature research on the precise TOTTA spatial visual guidance in MR are: "What are the existing approaches in literature?", "How are the TOTTA widgets designed?" and "How are TOTTA widgets evaluated?".

Being a multidisciplinary and cross-domain problem, the query definition is divided into four categories: "spatiality," "task," "technology," and "objective" Figure 2.1. the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used for conducting a systematic review [1].

This method is often used in conducting literature reviews [2]–[4]. The search was launched on the Scopus, ACM, and IEEE databases in August 2023. The PRISMA-based data collection

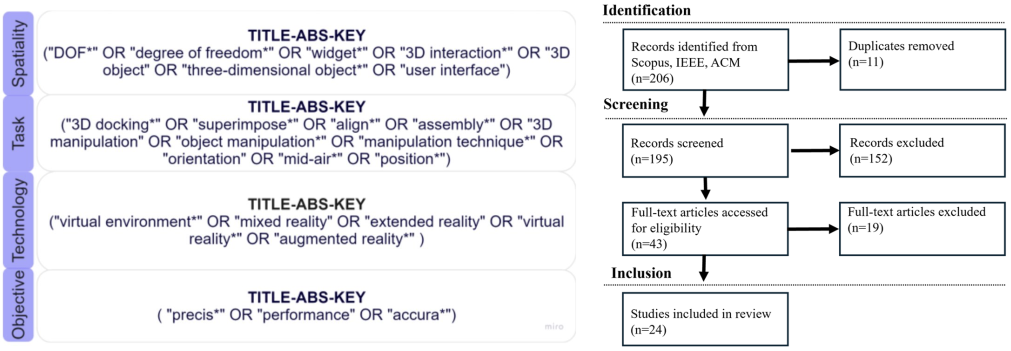

Figure 2.1: The research query of the systematic review (left), PRISMA flow chart approved by cite!!! (right).

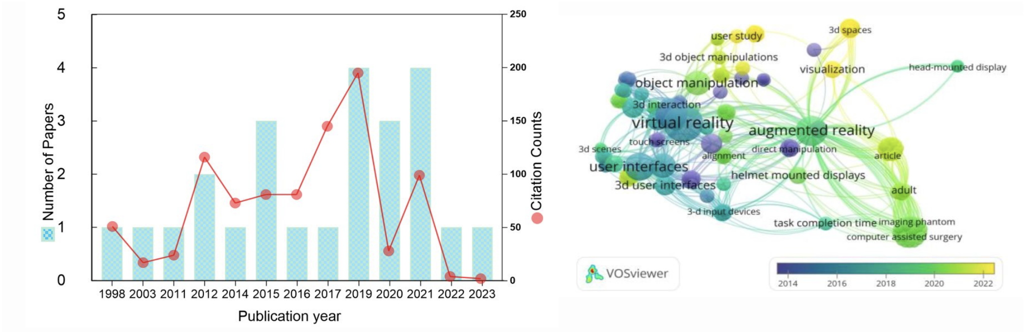

Figure 2.2: The 24 TOTTA paper's publication year and citations (left), bibliographic keywords connection of the TOTTA papers(right).

stage is summarized in Figure 2.1. From the initial 206 papers, papers that do not present or describe the widgets were eliminated, the ones that focus on only hardware devices without user interfaces and tasks that do not include a tool or target widgets. These aspects were essential in our systematic review. The selection pointed out the key connection between the papers; all present a spatial manipulation task of a visual real/virtual tool to a real/virtual target using TOTTA visual widgets. These criteria enabled detailed manual reading of the final selection of 24 papers in Table 2.1.

2.1.1 Bibliometric Analysis

The bibliometric analysis visualized the keywords of the selected papers using word clusters (Figure 2.2). This graph shows that "3D user interfaces" and "3D interaction" are the key topics, and "computer-assisted surgery" and "object manipulation" are common applications. The colors demonstrate how recent studies (yellow) VR first, then AR, later in green to "user studies "and visualization, as the effect of natural technology evolution and optimization. Figure 2.2 supports the topic's novelty and demonstrates a positive trend. More than 50 percent of the found literature papers have been published in the last five years, and the increased number of citations and the majority of the papers are conference proceedings (16/24 papers, 67%). The application domain is general in most of the cases (19/24 papers, 80%), with some verticalizations in medical (2) and industrial (3). This can be explained by the fact that TOTTA is a very common task, and these widgets can be useful in many domains.

Table 2.1: Summary of the selected papers' used technology, interaction, visualization, and tracking device.

No.	Authors	Technology	Interaction	Visualization Device	Tracking Device
1	Boritz et al. [5]	Desktop VR	Object-Mouse	CrystalEyes T	Fastrak Near
2	Fiorentino et al. [6]	Projected VR	HMD Controller	Vertical screen, Projectors	ART Near
3	Veit et al. [7]	VR	HMD Gesture-Touch	CrystalEyes CE-2	ART Far
4	Ragan et al. [8]	VR	HMD Controller	Virtual Research V8 HMD	Optitrack Near, Far
5	Raj et al. [9]	Desktop VR	Object Computer	Kinect v2	InterSense inertia cube3 Far
6	Ha et al. [10]	AR	HMD Gesture	ACCUPIX my bud	PTAMM camera tracking Near
7	Vuibert et al. [11]	Desktop VR	Gesture-Object	Vision RF shutter glass	Optitrack Flex: V100 Motion capture Far
8	Wang et al. [12]	VR	HMD Object-Touch	eMagin z800 HMD	PhaseSpace motion capture Near
9	Feng et al. [13]	Fish tank VR	Object-Touch	Nvidia 3D Vision glasses	Polhemus Fastrak Near
10	Mendes et al. [14]	VR	HMD Object-Touch	Gear VR, Samsung s6	Kinect v2 Near
11	Krichenbauer et al. [15]	VST-HMD	Object	Oculus Rift, OVR vision stereo	Leap Motion Near, Far
12	Ro et al. [16]	AR	HMD Gesture-Touch	HoloLens	Kinect v2 Far
13	Kim et al. [17]	VR	HMD Controller	Oculus Rift Consumer	Positional Near
14	Schlunsen et al. [18]	VR	HMD Controller	HTC Vive pro	Leap Motion Far
15	Heinrich et al. [19]	Projected AR	Object	Projector	Fusion track 500 Near
16	Sun et al. [20]	Web VR	Mouse Computer	NA	Far
17	Andersen et al. [21]	AR	HMD Gesture	HoloLens 1 6-DoF V	Far
18	Liu et al. [22]	VR	HMD Gaze	HTC Vive Pro-Eye	6Dof VR, eye tracking Far
19	Weiß et al. [23]	AR/VR/Projected AR	Object	HTC Vive, HoloLens, projector	Vuforia image target Near
20	Fuvattanasilp et al. [24]	Handheld AR	Touch	Apple iPad Pro (2017)	AR marker Far
21	Lee et al. [25]	VR	HMD Controller	HTC Vive	6-DoF VR Near, Far
22	Yu et al. [26]	VR	HMD Gaze	Pico Neo 2 Eye	6-DoF VR, eye tracking Far
23	Dastan et al. [27]	VR	HMD Controller	Oculus Quest 2	6-DoF VR Near
24	Ganias et al. [28]	VR	HMD Controller	HTC Vive Pro Eye	Two base stations Near

2.1.2 TOTTA Widgets in Literature

This section presents the key aspects of the TOTTA widget design in chronological order, along with the main research drivers and findings.

Boritz et al. [5] propose a direct midair TOTTA interface using a new tetrahedron-shaped physical input device. The TOTTA widgets, which mimic the input device, are two identical tetrahedrons (1.73cm height and 0.87cm width), with one face perpendicular to the base and with a checkerboard texture Figure 2.3. The user must align TO on TA geometric shapes. When the distance is less than a threshold (0.5 cm), a red box appears at the tip of the TA. They found higher positional error along z (front direction of depth) with the monoscopic display vs stereo.

Figure 2.3: Boritz et al. [5] use Tetrahedron, No: 1.

Fiorentino et al. [6] implement TO with a 3D Model - a simplified representation of the physical pen held by the user–; for TA, a green Box with colored 3D Axes Figure 2.4. With only a 3D positioning test, they found that difficulty varied with the target position: the targets in front of the user and above the head led to greater error.

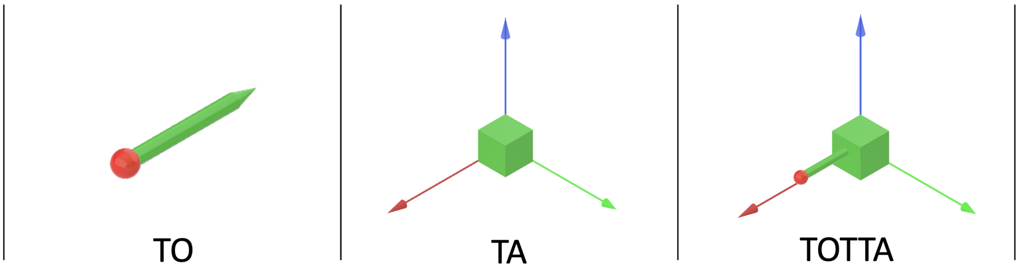

Figure 2.4: Fiorentino et al. [6] use Model TO, Box TA and Axis TA, No:2.

Veit et al. [7] investigate touch screen interactions with DOF separation (height axis vs. depth axis) using a monochromatic (green) 3D Axes TO (15 cm length) and a semi-transparent blue globe TA (7.5 cm radius). At collimation, the TO 3D Axes flash Figure 2.5. Results indicate that isolating the depth axis manipulation increases precision, while haptic cues do not improve user precision.

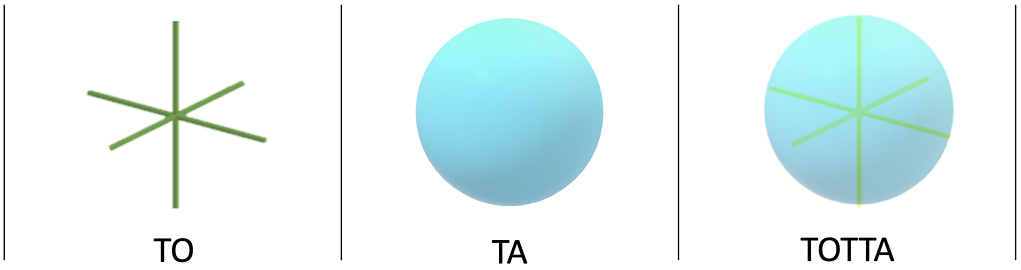

Figure 2.5: Veit et al. [7] use 3D Axes TO and Globe TA, No:3.

Ragan et al. [8] propose a multi-touch input device for TOTTA. They use two Boxes of different sizes: TO is opaque blue, and the TA is semi-transparent purple, with eight small gray spheres in the vertexes. As additional feedback, the spheres turned red when only a vertex was aligned and green when all eight were aligned Figure 2.6. They found that touch-based interfaces increased the task completion time compared to wand or joystick interactions.

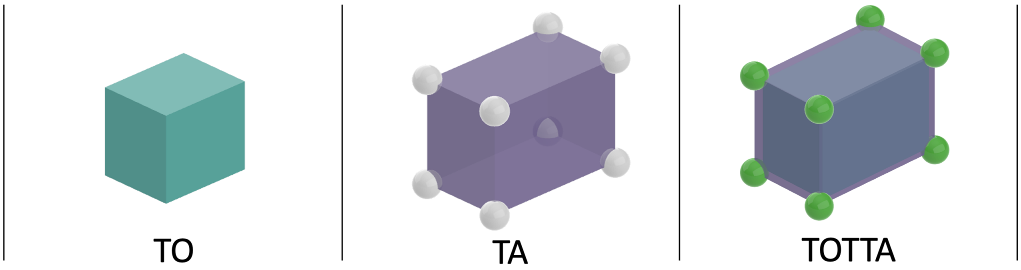

Figure 2.6: Ragan et al. [8] use Box No: 4.

Raj et al. [9] utilize two different colored 3D Axes: TO, purple, and TA, gray. Both 3DAxes had unique-colored spheres at the endpoints to match the orientation Figure 2.7. The results differed between participants' gender and video game experience. This research shows how the user's gender, avatar representation, and experience can influence performance. The self-avatar visualization resulted in a slightly faster rotation time than a sphere visualization of an avatar.

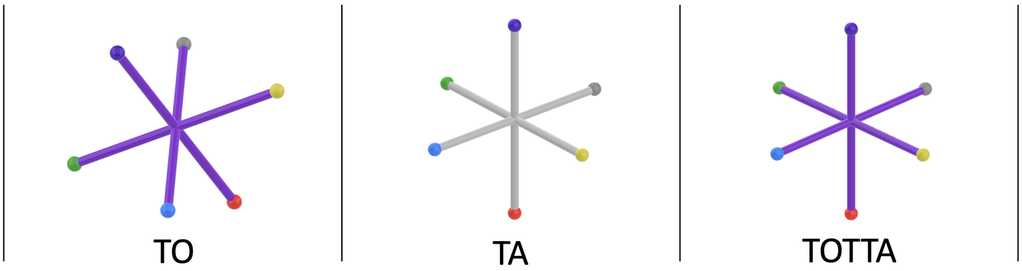

Figure 2.7: Raj et al. [9] use 3D Axes, No:5.

Ha et al. [10] implemented a bare-hand user interface with a green Box for TO and a blue Box for TA combined with semi-transparent grey guidelines and shadows where the lines intersect in the AR environment Figure 2.8. The TA Box turns red as the target achieves feedback. This design is interesting as it claims that anteroposterior depth visual feedback by shadows and guidelines enables precise manipulation.

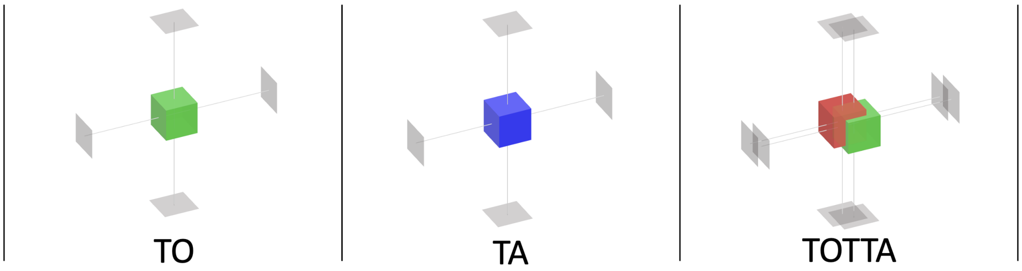

Figure 2.8: Ha et al. [10] use Box No: 6.

Vuibert et al. [11] compared the tetrahedrons versus two chair models in desktop VR; they use a pair of same-sized Tetrahedrons rendered as a colored wireframe Figure 2.9. TO has an opaque sphere in the center, and TA has a larger semi-transparent sphere. This research found that virtual 3D models can perform better (time and precision) than tetrahedrons, probably by leveraging natural human skills from the real world. However, the 3D Model must allow unique positional and angular collimation.

Wang et al. [12] developed an Object Impersonation metaphor that enables switching the DRIVE (avatar view on a tablet and tetrahedron's view on HMD) and VIEW methods (avatar view

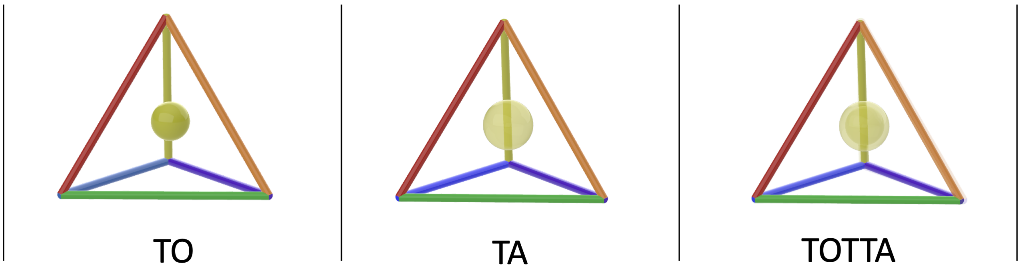

Figure 2.9: Vuibert et al. [11] use Tetrahedron, No: 7.

on HMD and tetrahedron's view on a tablet). They use a pair of same-size Tetrahedrons with small colored spheres in the vertexes and additional Crosshair Figure 2.10. This widget comprises two coplanar, perpendicular lines (forming a 2D cross) surrounded by concentric circles. TO is semi-transparent blue with gray edges and orange crosshair, and TA is non-transparent turquoise with non-transparent crosshair. The object impersonation method gave better orientational precision but required higher cognitive demand.

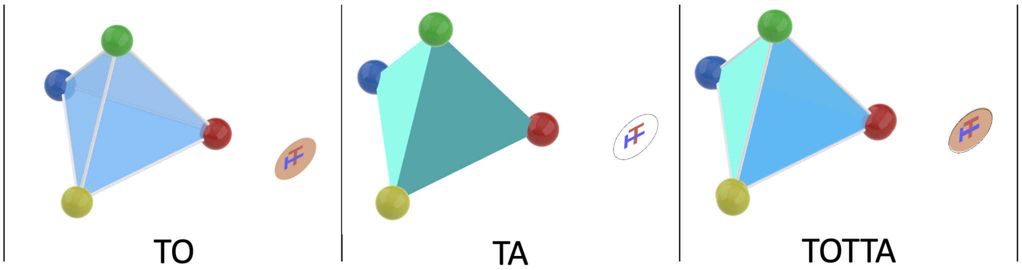

Figure 2.10: Wang et al. [12], Tetrahedron and Crosshair, No: 8.

Feng et al. [13] evaluate one-hand free vs novel two-handed input devices for 7 DOF manipulation techniques. The input device corresponds to virtual spherical cursors (blue-left, pink-right). They use Box TOTTA with colored faces, but different in size and frame color: red (TO) and white (TA) Figure 2.11. The virtual cursors are linked with an orange-colored cylinder "spindle" with a small red sphere mid-point. The technique's result is equivalent when the TOTTA size is the same and faster with their input device when the TOTTA size is different.

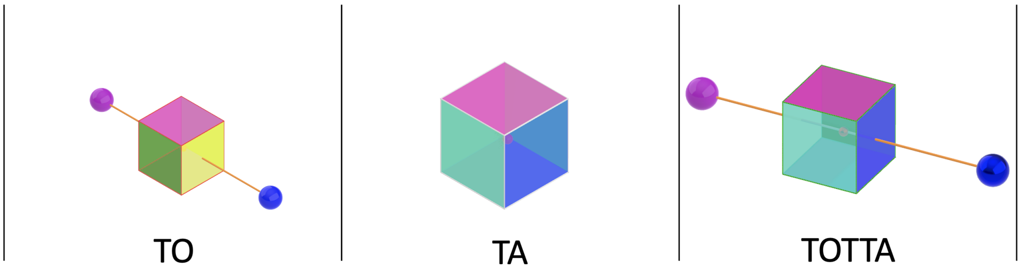

Figure 2.11: Feng et al. [13] use Box, No:9.

Mendes et al. [14] present an opaque 3D Model with colored 3D Axes with sphere endpoints for TO and a transparent 3D Model for TA Figure 2.12. Interactive secondary feedback is provided by the Model TO color, which gradually turns green with the distance from TA. An interesting aspect is that the 3D axes allow for the control of a single DOF. The PRISM technique dynamically adjusts between hand and object motion ratio. Experimentation demonstrated how DOF separation brings benefits but at the cost of task completion time.

Krichenbauer et al. [15] compare AR vs VR, TO as a composition of an opaque Box with a single red face textured with the number two, colored 3D Axes, and a wireframe-colored Globe. Figure 2.13. TA is a box like TO with different sizes, transparency, and dashed edges. The results

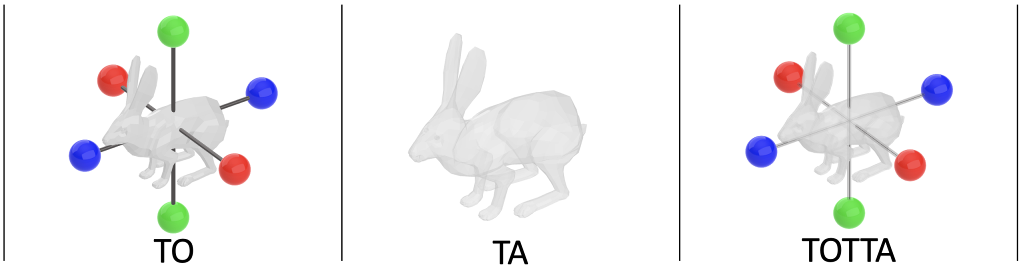

Figure 2.12: Mendes et al. [14],3D Axes, No: 10

claim that AR resulted in faster completion time than VR when using a 3D input device and mouse.

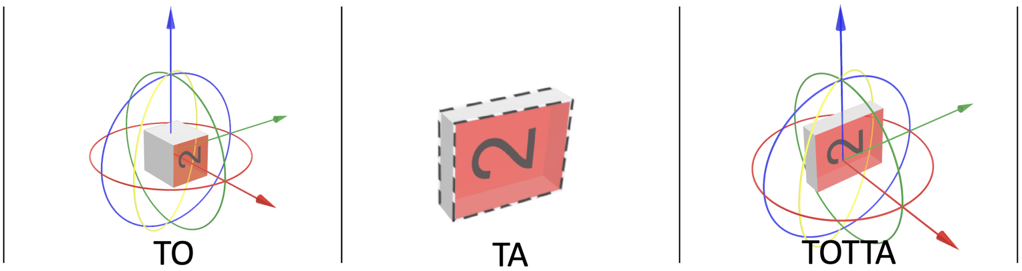

Figure 2.13: Krichenbauer et al. [15], 3D Axes/Globe/Box; No:11.

Ro et al. [16] present a novel physical input device using the Laser pointer metaphor AR pointer. The user collimates the Box TO (green, blue, red) remotely with a touch on the mobile device to a different size semitransparent TA Figure 2.14. The AR pointer performs better in task completion time than the direct free-hand 3D manipulation metaphor.

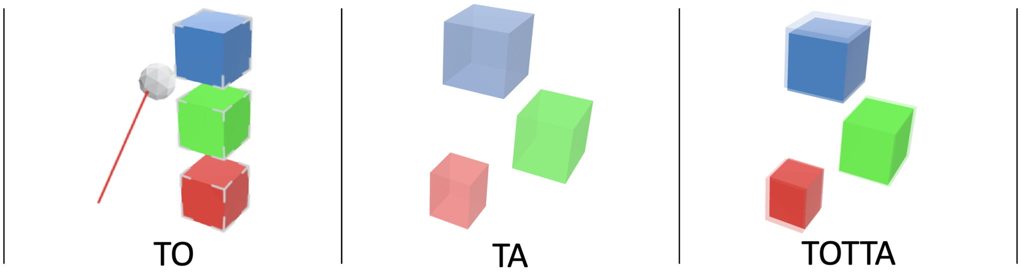

Figure 2.14: Ro et al. [16] use Box No: 12.

Kim et al. [17] compared “DOF separation (1DOF, only axis-handles)”, “without DOF separation (3DOF, only center-handle),” and “switchable DOF (1-DOF/2-DOF/3DOF, center, and axis-handles)” for mid-air manipulation. They utilize TO as a combination of a 3D Model (a teapot), colored 3D Planes, and colored 3D Axes with spheres in the endpoint Figure 2.15. TA is represented only as a semi-transparent 3D model. During manipulation, the constrained axis becomes yellow along lines or planes. The switchable DOF outperformed others in terms of time and precision efficiency.

Schlunsen et al. [18] evaluate free hand vs widget-based manipulation techniques and different multimodal cues for 3D manipulation of system control tasks. Green framed gray Box TO with 3D Axes TO (translation) with spheres in the endpoints and gray framed Globe TO (rotation) is used [18]. TA is a brown-framed yellow box. The free-hand manipulation resulted in faster and most preferred by the participants. They claim that multimodal feedback (audio) improved the user experience.

Heinrich et al. [19] compare three visual widgets (circle, the crosshair, and the arrow concept) for AR-supported medical needle insertion Figure 2.17. They use different-sized 2D Crosshair

Figure 2.15: Kim et al. [17] use 3D Axes/Plane/Model, No: 13.

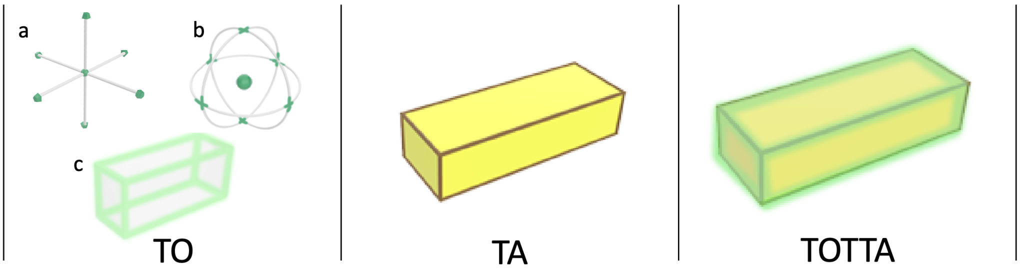

Figure 2.16: Schlunsen et al. [18], 3D Axes/Globe/Box, No: 14.

TOTTA, small crosshair TO (color change red-orange-green), and bigger crosshair (transparent-yellow-green- red for depth feedback). Each concept has distinct color mapping and indicator scaling. The Crosshair outperformed in orientation and depth parameters. The results for the color and indicator scaling factors are less consistent.

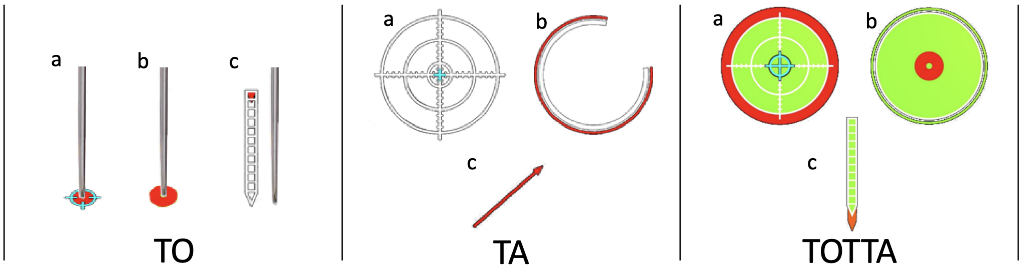

Figure 2.17: Schlunsen et al. [19], 3D Axes/Globe/Box, No: 15.

Sun et al. [20] compare DOF manipulation modes in WebVR to explore user workload and task performance effects. TO use colored 3D Axes (translation) with cones in the endpoints and Globe TO (rotation) with three wireframes with different colored rings with spheres of interaction points Figure 2.18. The manipulated axis appeared yellow while others disappeared (1DOF). Multiple DOFs provide less perceived workload and higher presence. The results indicated that users feel less workload or more presence and tend to spend less time completing tasks on WebVR.

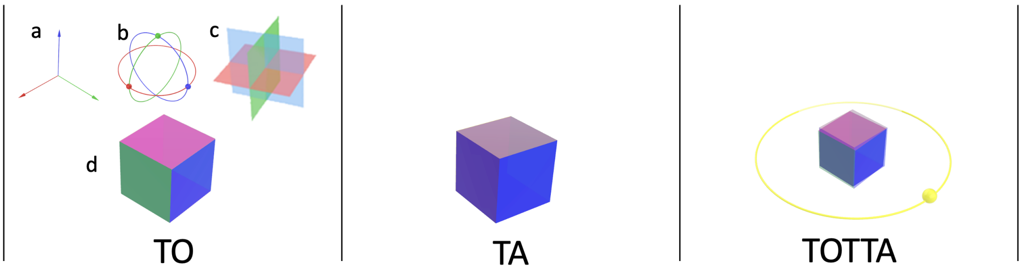

Figure 2.18: Sun et al. [20] use Sphere/Axes/Plane, No: 16.

Andersen et al. [21] elaborate on three semi-transparent widget designs for mid-air interaction. The 3D Axes TOTTA, Crosshair TOTTA (white and red), and triangular pyramid TOTTA Figure 2.19. The crosshair and triangular TOTTA have the shortest alignment time. In contrast, 3D Axes TOTTA performs best in translation and rotation errors. A novel aspect is that visual elements' size affects how far the user extends the arm, influencing torque forces.

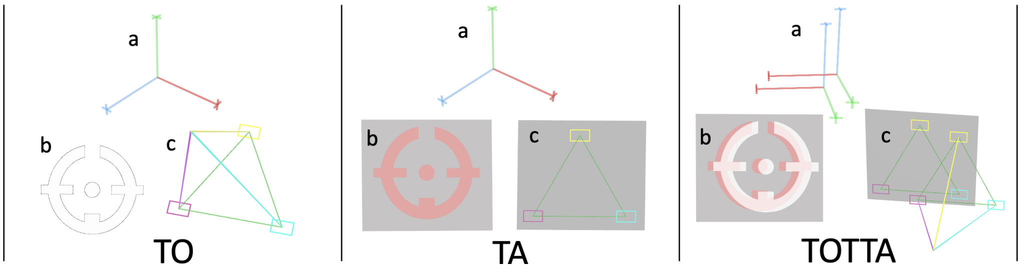

Figure 2.19: Andersen et al. [21] use Crosshair, No: 17.

Liu et al. [22] evaluate which type of gaze-based manipulations (eye vs. head) performs best when combined with OrthoGaze. OrthoGaze allows the user to manipulate gray Box TO using the orthogonal Planes TO. The TA is the green-colored Box TA Figure 2.20. During TOTTA, the gaze-selected Plane activates, and the user adjusts the 2-DoF position by looking at the target location and confirming placement through a gaze dwell. The eye gaze results are more accurate than the head gaze for continuous aiming.

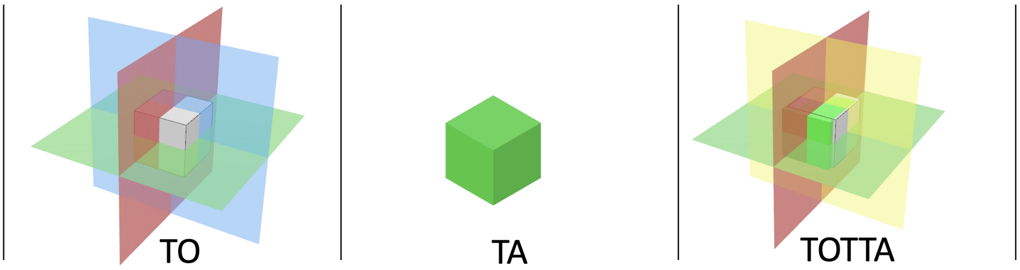

Figure 2.20: Liu et al. [22] use Box and Plane, No: 18.

Weiss et al. [23] investigate DIY tasks such as woodworking (drill, saw, and screw) using various levels of guidance: 2D video instructions, VR, and AR. They use distinct-size Crosshairs for TO and TA Figure 2.21. The TOTTA gives dynamic feedback to the user to avoid user error during drilling. The results indicate that context-aware situated visualizations are less likely to rely on empirical methods.

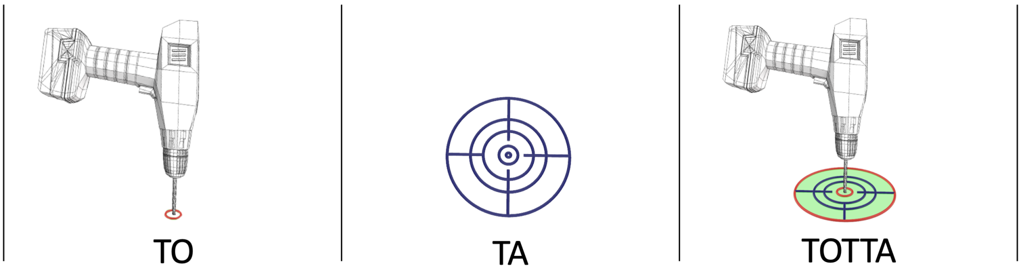

Figure 2.21: Weiss et al. [23] use Crosshair, No: 19.

Fuvattanasilp et al. [24] implemented SlidAR+, a novel handheld AR device (HAR) with an interaction method. They use a red-colored Line TO and a translucent, green-colored arrow with a thin blue line TA Figure 2.22. The user matches the TO (red arrow) with the TA (green arrow with the base of the virtual pillar). To align perfectly, a red line appears from the arrow TO tip to the TA, and the user slides TO using the Line. SlidAR+ resulted in faster task completion and is preferred by users.

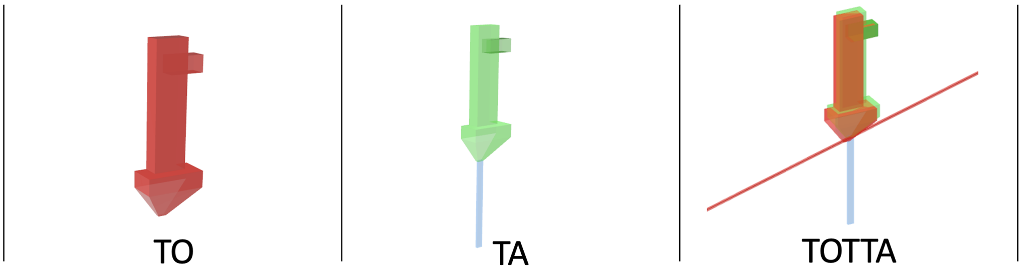

Figure 2.22: Fuvattanasilp et al. [24] use Line, No: 20.

Lee et al. [25] propose a novel near-field interaction metaphor for distant object manipulations. They compare widget-based metaphor with unimanual metaphor (one hand & scaled replicated model) and bimanual metaphor (both hand & scaled replicated model). The Box TO has eight pair-colored small spheres in the vertex points Figure 2.23. For translation, a colored 3D Axes TO is used with a small yellow cube visually indicating the manipulated axis and red text for numerical feedback. For rotation, a colored wireframe Globe TO with a sphere is used. TA is a white wireframe with colored spheres on vertex points. The unimanual metaphor has the highest efficiency, the widget-based metaphor has the slowest, and the bimanual metaphor, with a scaled replica, grants the lower movement. Interestingly, subjective impressions are most favorable with the bimanual metaphor.

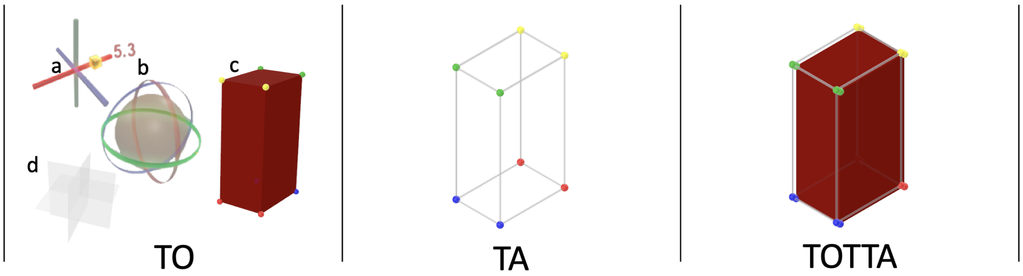

Figure 2.23: Lee et al.[25] Sphere/3D Axes/Plane TOTTA, No: 21.

Yu et al. [26] compare four gaze-supported interaction techniques: gaze grab, remote hand, 3D Magic gaze, and implicit gaze. They used a 3D Model for TO (a rabbit) and a transparent replica Figure 2.24. During the manipulation, the TO has a blue outline, and when the target is achieved, it turns red. The results indicate that gaze does not influence performance when the TO is in front of the user, but it can be useful for distant targets and larger spaces. The gaze input reduces the fatigue of the arms and potentially allows future TOTTA manipulation.

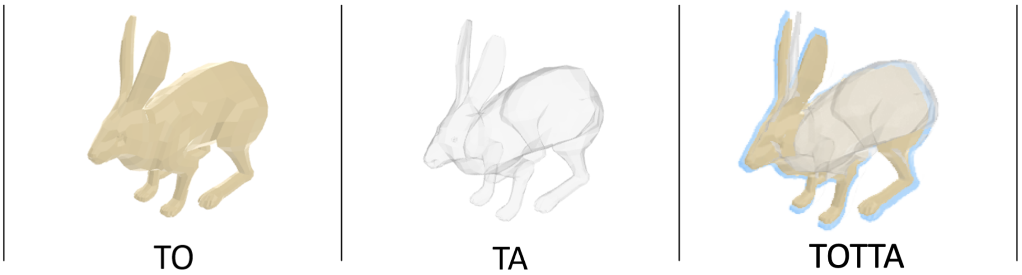

Figure 2.24: Yu et al. [26] Model TOTTA, No:22.

Dastan et al. [27] present a 5DOF guidance applied to dental implantology as the rotation along the drill axis is not influent. TO comprises three triangle pairs - colored differently for each direction- and two semi-circle pairs - colored differently for each rotation Figure 2.25. The pairs visualize in real time and amplify the position and rotation distance values. TA is a static green line with a concentrical cylinder. This approach leverages human reification from Gestalt theory [34], seeking a quick, pre-attentive reaction. Their method performed better in angular (with major effects) and positional precision and accuracy, with less mental demand and frustration than the literature. However, this gain is obtained with a significant increase in task time and physical demand.

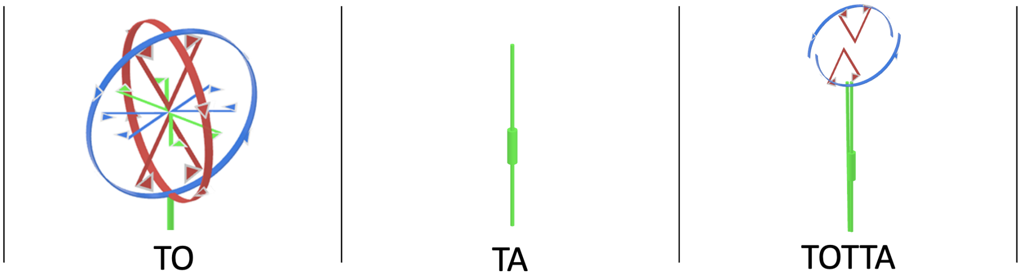

Figure 2.25: Dastan et al. Axes/Globe/Line TOTTA, No:23.

Ganias et al. [28] compare grasping visualizations, auto-pose (realistic grasp), single pose (hands do not penetrate with object), and disappearing hand (hand disappears). They used a colored Box for TO (solid) and a transparent replica for TA Figure 2.26. At the end of each positioning, the visual cue of the changed color was used (the yellow returned green). The results indicated no significant difference in user performance in any visualizations. The auto pose is a user preference and provides a stronger perceived sense.

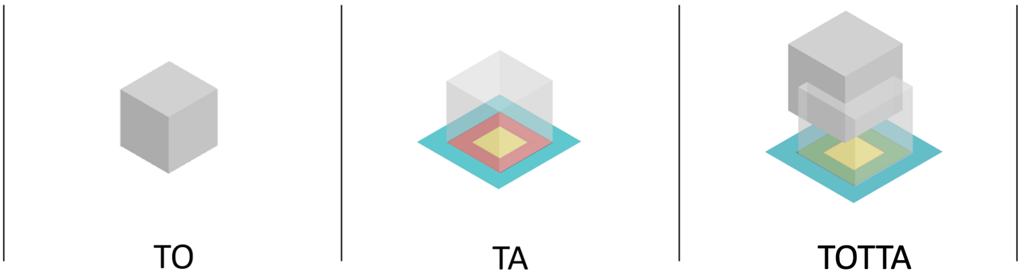

Figure 2.26: Ganias et al. [28] Box TOTTA, No:24.

2.2 Widget Desing Analysis

A key aspect of TOTTA widgets is the distance of interactions. Near-field interactions allow the ability to direct manipulation of tool and target in proximity and are advantageous for the precision of small-size objects. On the other hand, the far-field interactions rely on distant object manipulations beyond the user's arm reach, which is advantageous for large tools and target size and distance flexibility. There is no prevalence between the near-field (12/24 papers, 50%) or far-field interaction (9/24 papers, 37%), and few studies (3/24 papers, 13%) employ both Table 2.1. The TOTTA may require various levels of DOF, it requires superimposing or aiming. The most common widget guidance mechanic is the visual 3D superimposition of TO over TA (20/24 papers, 83%) Figure 2.28. A limited number also includes the scaling (8/24 papers, 33%) with the superimposing task, which consists of changing the size of the TO widget to match the TA. Visual scaling has no direct meaning for TOTTA collimation, even if it may have the potential to set some tool parameters (e.g., drill speed value). However, this usage is not envisioned in the selected papers. Few papers prefer the aiming task (4/24 papers, 17%), which provides a reference point for the user to aim and align the TO used for 5DOF tasks (e.g., needle insertion, drill positioning).

For a precise TOTTA, users receive multimodal guidance feedback associated with TOTTA widgets. At first glance, TOTTA visual widgets use basic shapes. However, each TOTTA

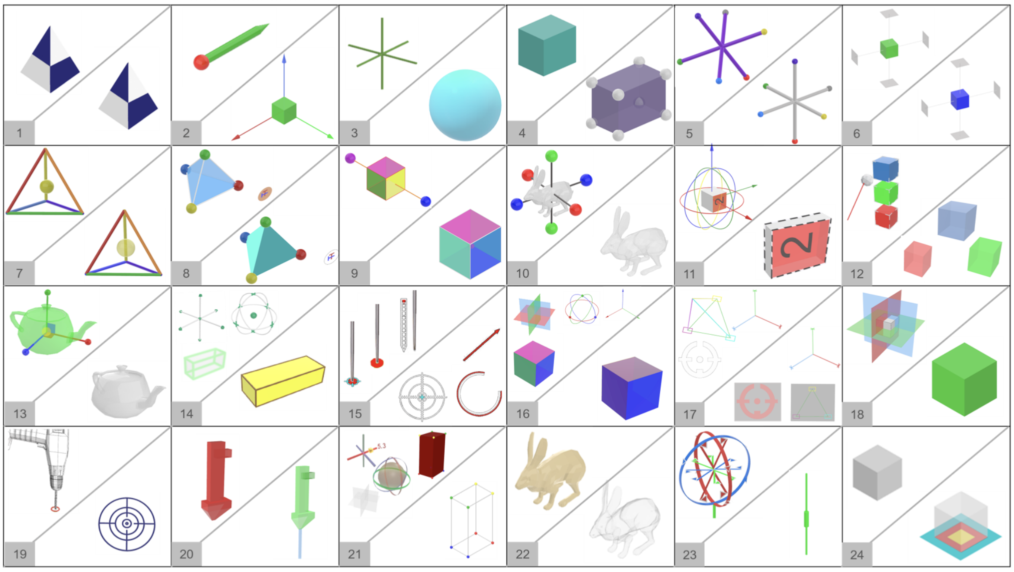

Figure 2.27: The Tool to Target (TOTTA) widget designs from the 24 papers analyzed chronologically. For each frame, the Tool widget (TO) is depicted at the top left, and the Target widget (TA) at the bottom right.

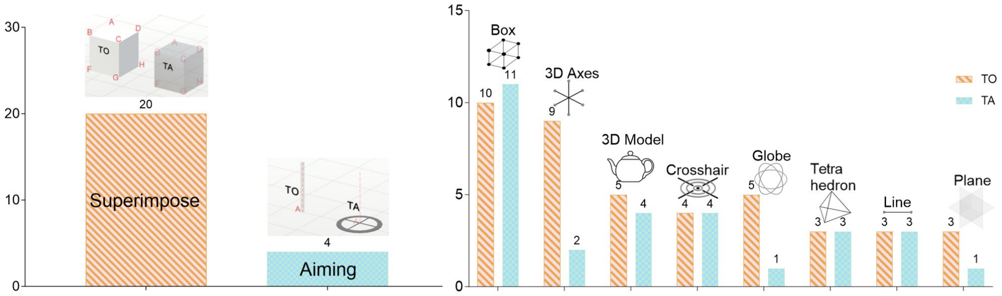

Figure 2.28: Two main TOTTA tasks in the evaluations (right), Eight different visual designs were used for the TO and TA widgets (left).

representation is unique in detail. Therefore, the whole design gathered in a TOTTA widget cluster, resulting in 70 different graphical designs (Figure 2.27).

In the next subsections, widget guidance mechanics were analyzed through their feedback to the user. TOTTA widget design was divided into feedback factors: “Collimation Feedback,” “End of task feedback,” and lastly, “During manipulation feedback.”

2.2.1 Collimation Feedback

The TO and TA shapes must provide positional and orientation graphical/geometrical clues for unique collimation configuration. This aspect is not trivial and is key in widget design. Eight diverse types of shapes were found: Box, 3D Axes, 3D Model, Crosshair, Globe, Tetrahedron, Lines, and Planes (Figure 2.28). The box is the most preferred geometry (21/70 design, 30%, 10 TO/11 TA). It is simple, has predictable orthogonal angles, and is easy to implement in all graphical engines. The Box design is preferred by 10/24 papers [7], [9], [12], [15]–[17], [19], [21], [24], [28] Figure 2.28). It’s also curious how boxes are used in physical child toys to learn motor skills. Box widgets with different dimensions can provide unique positional reference and partial angular. For angular, unique primary Box is supported by additional shapes or different colored/textured faces, edge styles, or sizes. 3D Axes are also common (11/70 design, 16%, 9TO/2TA), with a clear and familiar design for CAD users and gamers. The 3D Axis design is preferred by 9/24 papers [6], [8], [13], [14], [17], [19], [20], [24], [27] Figure 2.28. The presence of a center supports positional placement, and the orthogonal lines facilitate angular arrangements.

TO and TA are differentiated by colors or additional geometries, like spheres in the vertices. 3D Models (9/70 design, 13%, 5TO/4TA) (e.g., rabbit, teapot, arrow) instead of basic geometries. This design is preferred by 5/24 papers [13], [15], [16], [23], [25] Figure 2.28. TO and TA 3D Models are commonly differentiated by color and transparency. However, the choice of a specific model is limited as some 3D models may be inefficient in positional and orientational guidance. Therefore, they are substandard or rarely used by the end user. Crosshair (8/70 design, 11%, 4TO/4TA) is common in aviation, military, and healthcare interfaces. The Crosshair design was chosen from 4/24 papers [11], [18], [20], [22] Figure 2.28. Planar or 3D crosshairs are used in spatial interactions with reduced DOF, like needle insertion and drilling. Globe (6/70 design, 9%, 5TO/1TA) is a familiar widget design for desktop applications and games. Interestingly, 6/24 papers Figure 2.28 preferred Globe and they are often preferred singularly only TO or only TA without having them together in the task [6], [14], [17], [24], [27]. Globe is often represented as wireframe rings or semi-transparent to avoid visual occlusion. The tetrahedron (6/70 design, 9%, 3TO/3TA) is geometrically the simplest (having minimum entities) shape for the TOTTA widget. 3/24 papers use it [5], [11], [12] Figure 2.28. The corners help with orientation but are less familiar than the other shapes and have no orthogonal angles. Line (6/70 design, 9%, 4TO/2TA)) can provide single DOF guidance concerning mid/end points by distinctive styles (dashed, solid, transparent, or color). However, a combination of elements is required to be functional in the 3D space. The Line widget is preferred by 4/24 papers [12], [15], [20], [25] Figure 2.28. Planes (4/70 design, 6%, 2TO/1TA) are usually represented in three perpendicular surfaces. Their intersection can also generate 3D axes. However, Planes are less intuitive and more prone to visual occlusion than others. The Planes are preferred by 4/24 papers [17], [20], [22], [25] Figure 2.28. Some other visual representation methods are used in TOTTA to support collimation feedback Figure 2.28.

As theorized by perception, the same or similar shapes for TO and TA are used principally (22/24 papers, 92%). To further distinguish the tools from the targets, colored minor parts of widgets (such as frames/vertices/faces) (18/24 papers, 75%) or entirely colored widgets (17/24 papers, 71%) are used frequently. Transparency (16/24 paper, 67%) is also used to reduce visual cluttering and enhance depth perception during collimation. Following, TO and TA pairs are differentiated by containing additional/different geometrical elements like small spheres and cubes (14/24 papers, 59%). Some preferred (13/24 papers, 54%) more than one design of widgets, defined as "Mixed widgets" [17], [18], [25]. They have used the composition of shapes (from Fig 31), requiring more cues for guidance—even redundant in some cases—since they can result in more complexity. Finally, the widget sizes (11/24 papers, 46%) distinguish TO from TA, especially if the task requires resizing.

2.2.2 During Manipulation Feedback

This feedback supports the user during the TOTTA task through continuous guidance feedback Figure 2.29. Only 14/24 literature papers are used to manipulate continuous feedback; they are interactive and not just signals. Most TOTTA designs use continuous color change (e.g., red-orange-green) to convey guidance (9/24 papers, 13%). Text feedback (2/24 papers, 13%) is also preferred to indicate the real-time error values. Some use sonification (2/24 papers, 8%), which is a simultaneously generated sound (e.g., drums with variable rhythm) to guide the user interactively [11], [18]. Text feedback can provide precision control during TOTTA. However, since there is a continuous change of text in the field of view, it may frustrate the user or cause a high task load. As a dynamic novel approach, error visualization (1/24 papers, 4%) is used during the manipulation. This approach promises intuitive feedback; it allows dynamic visualization of the target distance by widgets' forms of distance [27]. Another unique aspect is that the widgets disappear at the target threshold, reducing clutter. The widgets' more dynamic and complex behavior is demonstrated to improve user performance but at the cost of physical and cognitive demand. This aspect of widget design has an undisclosed potential to guide the user along the interaction in addition to collimation.

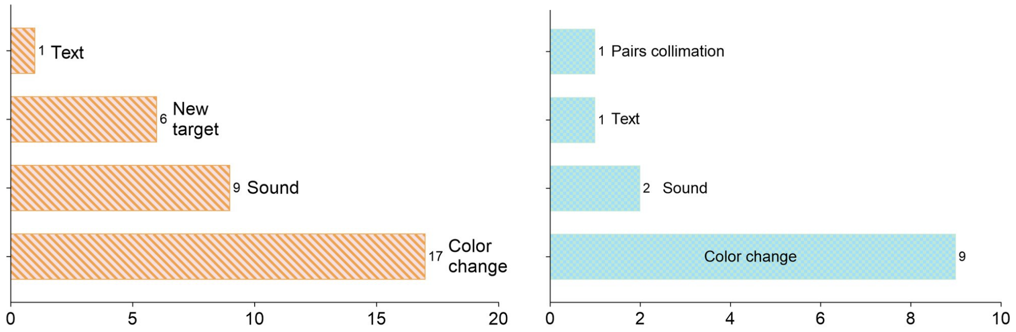

Figure 2.29: TA reached Feedback at the end of the task (left), During manipulation, continuous feedback (right).

2.2.3 TA Reached Feedback

As the TO and TA shapes begin to superimpose, visual collimation feedback becomes increasingly inefficient. Therefore, "supplementary" feedback is often provided concurrently with the collimation Figure 2.29. This feedback conveys the end-of-task information as signals and they are triggered at the TOTTA positional and rotational distance threshold, probably to substitute haptic feedback (e.g. vibration) [10], [17], [18], [22]. Commonly, instant color change is used after task completion (17/24 papers, 71%) as it is intuitive for the user and is easy to implement. Further, at the collimation event, playing a completion sound (9/24 papers, 38%) followed by a new object/target appearance (6/24 papers, 25%) [12] and text flash (1/24 papers, 4%) "Right There!".

2.3 Evaluation Methods

TOTTA widgets perform differently and can be physically and mentally demanding for the user. Not much research has been done to highlight how the literature compares and evaluates different TOTTA designs. Therefore, in this section, literature evaluation methods were analyzed in four subsections: research questions, Participants, Procedure, and Metrics.

2.3.1 Research Questions

Common literature research questions are manipulation methods (10/24 papers, 42%): DOF separation, multi-level DOF, learning (knowledge retention, skill acquisition, and transferability), or user experience evaluation (presence and engagement), Figure 2.30. A secondary research question concerns interaction devices (5/24 papers, 21%), such as hand-held controllers, finger-tracking, and eye-tracking, and their effect on user experience regarding usability, user satisfaction, and performance. A third common research question concerns visualization techniques (5/24 papers, 21%) and the effects of AR/VR user experience on presence and engagement. Our research discovers that the research questions on widget visual design are limited (3/24 papers, 13%) despite its significant impact on the user experience and performance. Other research questions are specific: gender video game experience affects self-avatar representation (1/24 papers, 4%) on the 3D manipulation task.

2.3.2 Participants

Within-subject (20/24 papers, 83%) is the most utilized methodology among the literature papers. The average number of participants is 21 +—SD 12.9, with a minimum age of 18 and a maximum age of 50. Most are right-handed (92%), young (SD 3.1, mean 25.8), and male (65%) Figure 2.30. The majority are student participants (90%), some unpaid volunteers (4 /24 papers), and some paid (4/ 24 papers), while the rest is not specified.

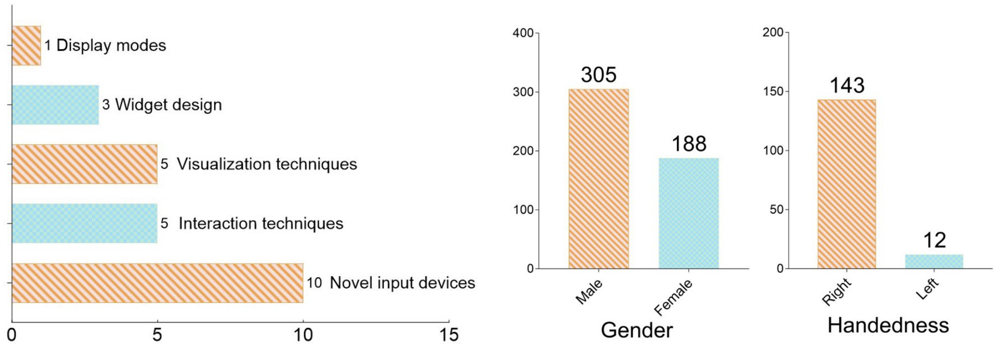

Figure 2.30: Research Questions of the TOTTA papers (left), Participants' demographic information (right).

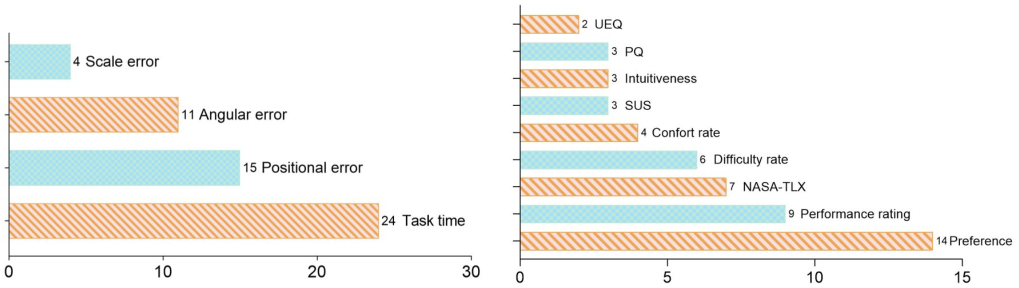

Figure 2.31: Quantitative metrics (left), Qualitative metrics (right).

2.3.3 Procedure

TOTTA validations are more commonly tested in VR (19/24 papers, 79%) than in AR. Twelve papers use VR HMD, five use desktop VR, three AR HMD, two use Projected AR, one uses Fish Tank VR, one uses VST-HMD, and one uses hand-held AR, as shown in Table 2.1. Often, the participants are provided with a hand-held device (17/24 papers, 71%) since it simulates the feeling of a TO being picked up or provides physical feedback when interacting with an input device or controller, Table 2.1. A custom-made object input device is the most preferred (9/24 papers, %37), followed by a controller (7/29 papers, %29) and mouse (2/24 papers, %8) input devices. Moreover, 5/24 papers (%21) involved a free-hand interaction, and 2/24 papers (%8) included a gaze interaction as well. In some cases, the participants were also provided with virtual avatars and input device representation (8/24 papers, 33%), influencing self-perception and the sense of presence in mixed realities.

2.3.4 Metrics

The literature papers measure performance, acceptance, and preference using similar metrics. The most inquired metric is task completion time (24/24 papers, 100%), followed by subjective data (20/24 papers, 83%), positional error (15/24 papers, 63%), angular error (11/24 papers, 46%), scale error (4/24 papers, 79%), and count (e.g., attempts, click) (4/24 papers, 17%) Figure 2.31. Subjective data was analyzed since it is essential for comprehensively understanding the user experience, needs, emotions, and behaviors collected during the experiment. The most investigated metric is user preference (14/24 papers, 58%), followed by the perceived performance (9/24 papers, 38%), NASA-TLX (7/24 papers, 29%), difficulty rate (6/24 papers, 25%), comfort rate (6/24 papers, 25%), SUS (4/24 papers, 17%), intuitiveness (4/24 papers, 17%), PQ-presence questionnaire (3/24, 13%), UEQ (2/24 papers, Figure 2.31. The least used metrics are AttrakDiff (1/24 papers, 5%), ARI (1/24 papers, 4%), and HARUS (1/24 papers, 4%).

2.4 Discussion

This systematic review showed that TOTTA widget designs are non-standard and differ in design, feedback, and interaction. In all studies, the TOTTA manipulation is supported by the Gestalt theory's visual overlap or cognitive psychology as a "collimation feedback," intuitive and pre-attentive feedback. The visual overlap of similar basic shapes is supported by reification, a pre-attentive human capability of interpreting visual information as theorized by the Gestalt laws, such as proximity, closure, similarity, and continuation. This aspect is not always supported from a theoretical cognitive point of view in the studies. Box, 3D Axis, and 3D Models are the most preferred ones. However, geometries that are missing a center (e.g., wireframe Box) can have problems with precise positioning. The alignment of the same basic-shaped TO and TA presents the challenge of differentiating them. Some evaluated approaches are frames/vertices/faces color or style (75%), different-colored TO/TA (71%), transparency (67%), additional shapes (59%), multiple widgets (54%), and size (46%). Using colored, partial elements and transparency, TO and TA are differentiated. Transparency can also be beneficial for reducing visual occlusion during the TOTTA task. Although some patterns are visible and probably lead to effective solutions, few studies provide scientific ground for visual and interaction design. It's argued that a deeper comprehension of the perception of shapes (e.g., Gestalt theories) can lead to better results in terms of performance and usability. Another aspect is the common design of the continuous "during manipulation feedback." Sonification and animations can bring large margins of improvement. The latest papers are evolving from the one-time signal at goal reach to a potentially more effective, dynamic, and responsive guidance method. Another key finding is the lack of a well-established golden standard and direct comparisons of the present widgets or a partial set. The hardware systems used in the selected papers vary in terms of immersion, tracking, and visual quality, deeply impacting the resulting experience, user performances, and acceptance. The TOTTA validation methods found in this systematic review use quite different -thus not comparable-experiment designs (target configuration, avatar, background, etc.), and some biases were spotted (VR is more tested than AR, right-handed, and male participants). Another aspect to highlight is that the accessibility issues are not investigated or mitigated (e.g., color code and color blindness), and none of the studies reviewed addressed this topic.

2.4.1 Limitations and Future Works

This study acknowledges its limitations because no previous research has been done in the literature to analyze the TOTTA widget design and evaluation methods. Papers that required a specific tool to align targets using visual widgets were examined. Tasks such as assembly were excluded since the user searches for tools and targets in the environment and constructs a whole. This limitation allows us to analyze each method deeply. For future works, it is important to evaluate the possible trade-off between the widget complexity and the cognitive overload as experienced in some experiments [12], [27]. It's supported that to achieve better performance, as requested by the industry, widget behavior will increase in complexity, and the future challenge is to balance this with users' cognitive overload.

Also, DOF separation improved user precision, so it may be investigated better as a design solution in future studies. On the grounds of this study, here below is drawn the future TOTTA research:

- •Define and implement a standard experiment framework.
- •Equally compare the existing TOTTA widgets.
- •Improve widget design by perception theory.
- •Improve widgets with continuous guidance.
- •Enforce diversity in user tests.

2.4.2 Key Findings

Some main research outcomes and key findings approved by TOTTA papers are presented below, considering that they are valid in the specific context, widget design, and experimental conditions.

- •TOTTA stereoscopic performs better than monoscopic view [5].
- •6DOF direct hand manipulations [8], [18], DOF separation [7], [14], switchable DOF [17], increased precision, completion time, and qualitative results.
- •Self-avatar visualizations reduce task time [9], and participants preferred the semi-transparent hand [10].
- •Object impersonation (user embodiment in TO) provides better orientational error but increases cognitive demand than DRIVE and VIEW metaphors [12].
- •If TO vs. TA sizes differ (the user must also apply to scale), the physical input device influences the task precision and time, and bimanual interactions are better suited than unimanual [13].
- •The participants perform faster in AR than in VR with a 3D input device [15].
- •Free-hand manipulation is faster than widget-based manipulation and is preferred by the participants, and multimodal cues improve the user experience [18].
- •The 2D crosshair performs better than the 2D arrow for translation and rotation [19]. 3D Model TOTTA performs better than 3D Axes/Globe [25].
- •The tetrahedron shape has better orientational precision, but the task time increases [11] compared to the model shape.
- •Gaze-based manipulation causes more fatigue than controller-based manipulation [22].

2.5 Chapter Conclusion

In conclusion, this chapter underscores the critical need for comprehensive standards and more inclusive testing methodologies in the study and design of TOTTA widgets. The main contributions of this chapter are as follows:

This research has successfully defined the TOTTA manipulation problem and demonstrated its importance across various domains, from surgical implantology to industrial applications. A systematic review was conducted, starting with 206 papers, from which 24 were selected for in-depth analysis of dedicated TOTTA widgets. The review presents existing approaches, analyzes the characteristics of TOTTA widget designs, and evaluates the methodologies used.

The key findings from the selected studies highlight existing gaps and provide important context for future research. This study offers valuable perspectives for researchers working in fields where precise tool-to-target object manipulation is required, such as medicine, aviation, industry, and retail.

The research concludes by emphasizing the necessity of addressing the TOTTA problem in the context of Mixed Reality (MR) systems. A standardized but flexible evaluation methodology is essential, accommodating the diverse implementations of MR systems in various scientific and practical domains.

Looking forward, the next chapter on state-of-the-art analyses of augmented dental tool manipulation widgets is pivotal. By applying the principles and findings from the TOTTA review, the next chapter will focus on applying these principles in the dental field, particularly in MR drill positioning widgets for dental tool manipulation. This chapter will build upon the groundwork, providing insights into how TOTTA systems can enhance precision in the medical field and guide future developments in tool to target manipulation widgets.

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Chapter 3

Precise Surgical Tool Manipulation Widgets in Dentistry Case Study

Chapter Summary

This chapter examines key studies in the dentistry field, investigating various systems, including those utilizing head-mounted displays (HMD), tablet-based devices, and marker-less navigation techniques. It evaluates these systems' strengths, limitations, and results, particularly their impact on surgical precision, user comfort, and overall effectiveness in dental procedures. The chapter discusses the challenges in achieving high-accuracy navigation and highlights the potential for further advancements in MR technologies to enhance the outcomes of dental surgeries.

Furthermore, this chapter establishes a foundation for developing next-generation MR-based drill tool manipulation widgets. By critically analyzing existing systems and their approaches, it seeks to identify the gaps and opportunities necessary to design innovative MR solutions that improve precision and usability in dental procedures.

This review serves as a baseline for the following chapters, providing essential insights that will guide the creation of an advanced MR approach for drill tool manipulation widgets. The findings and principles discussed here will serve as a critical reference point in the subsequent chapters, where new methodologies will be proposed and tested to further advance the integration of MR technologies into dental surgeries.

3.1 State of Art Analyses

Mixed Reality (MR) is proven in the literature to support precise spatial dental drill positioning by superimposing 3D widgets. Despite this, the related knowledge about widget's visual design and interactive user feedback is still limited. Recent advancements in spatial technologies have led to significant improvements in the accuracy and effectiveness of dental surgeries, particularly in implantology. A wide range of mostly AR-based systems has been proposed, each designed to address challenges like real-time navigation, accuracy, user experience, and hardware requirements Table 3.1 and Figure 3.2. Below is a detailed discussion of the key studies in this area, highlighting their methodologies, contributions, and limitations.

Ferronato et al.. introduced a novel AR system tailored for endodontic procedures. This system uses a tablet (iPad Pro 2020) to display augmented data, where the surgical target axis and reference points are superimposed over the patient's anatomical structures. Notably, their system does not rely on physical markers, making it a marker-less solution that simplifies the setup process. They integrated cone-beam computed tomography (CBCT) volumes into the system, offering a highly detailed 3D representation of the patient's anatomy. The UI displays static reference points and a red target axis that helps guide the surgical tool. In their experiment, which involved 90 drilling tasks across phantom and 3D-printed models, they found that the system provided positional errors of 0.51 mm and 0.77 mm, with an average angular deviation of 8.5°. While these results are promising, the system's performance could be improved by reducing angular deviations, which were notably higher compared to other AR-based systems [1].

Ma et al. developed an AR tool manipulation system that utilizes an IV overlay device using a different approach. This system superimposes various virtual elements—such as the tool axis, target axis, and implant path—directly onto the surgical field. A key feature of this system is its comparison of AR-assisted guidance with a non-guided method based on the dentist's experience. Their results indicated that the AR system significantly improved positional accuracy, reducing the positional error from 1.63 mm (non-guided) to 1.25 mm (AR-guided). Additionally, the rotational error decreased from 6.10° to 4.03°. This study confirms that AR guidance can enhance precision during dental surgeries. However, the system's reliance on bulky trackers led to discomfort for the volunteers, raising concerns about its practical usability in clinical settings [2].

Song et al. introduced the first head-mounted display (HMD)-based AR system designed for endodontic procedures. Their system integrates both visual and auditory feedback to guide the dentist. The visual feedback consists of dynamic disks that change in size and color to represent key factors such as tool depth, distance to target, and tool orientation. Additionally, auditory cues further enhance the user's awareness of tool manipulation. Their experiments, conducted on a scaled tooth model using HoloLens 2, showed positional errors ranging from 3.6 mm to 32.2 mm and rotational errors between 2.15° and 45.10°. While the wide range of errors suggests that the system still has room for improvement, the authors claimed that integrating both visual and audio feedback made the system more intuitive and reduced decision-making time for the dentist. However, the variability in error suggests that more consistent accuracy may be achieved with refined calibration and tracking methods [3].

Lin et al. proposed a hybrid AR system that combines augmented reality with traditional surgical templates. This system enhances dental surgery by displaying the drill axis, tooltip, implant path, and anatomical structures like the mandibular nerve over the surgical area. Integrating AR with traditional templates offers a balance between modern technology and established surgical practices. Their study demonstrated improved implant placement accuracy with positional errors of 0.5 mm for mandibular and maxillary implants. The angular deviations were reported to be 2.7° for mandibular and 3.3° for maxillary implants. The system uses world-relative tracking, ensuring the AR projections align accurately with the patient's anatomy during the procedure. However, the dependence on a traditional surgical template limits the system's flexibility compared to markerless systems [4].

Wang's study introduced a marker-free image registration technique using a projector-based AR system for dental surgery. This approach eliminates the need for additional markers, simplifies the setup, and improves ease of use during procedures. The AR system superimposes the drill tooltip and trajectory axis onto the phantom model, allowing real-time guidance during surgery. While the study did not provide specific error metrics, the key innovation of this system was its marker-free registration method, which reduces setup time and eliminates the potential for errors caused by misalignment of physical markers. However, the lack of detailed accuracy data makes it difficult to assess this approach's full potential and performance compared to other AR navigation systems [5].

Katic et al. developed a context-aware AR dental implant system, offering two visualizations: one that directly overlays the surgical field with relevant data and another that fixes information in a static position. This flexibility in the visualization setup allows for a more tailored approach to the surgical environment, adapting to the surgeon's needs during the procedure. Using Sony HMZ-T1 HMD goggles, the system was tested in a cadaver experiment, where it demonstrated significant improvements in positional accuracy, with errors reduced to as low as 1.1 mm. However, the reliance on specific HMD hardware may restrict the accessibility of this system in clinical environments, especially when alternative devices are not available or practical for use in real-world surgery [6].

Tao and colleagues conducted a study comparing AR-based navigation with traditional dynamic screen navigation (DSN). Their experiments, involving 242 implants placed by a single surgeon using HoloLens 2, revealed that both systems performed similarly regarding positional accuracy. The positional error for AR-based navigation was 1.31 ± 0.67 mm, compared to 1.18 ± 0.59 mm for DSN. However, the AR system showed slightly higher angular deviations, with an error of 3.72 ± 2.13° for AR and 3.1 ± 1.56° for DSN. The study concluded that both systems performed similarly for positional errors but highlighted that AR-based navigation may present higher angular deviations, suggesting that while AR has potential, further development is needed to refine its precision [7].

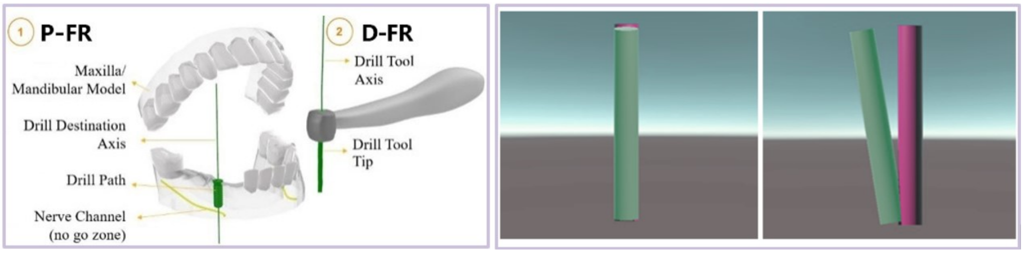

Figure 3.1: Reference of visual assets present in the State of Art (left image), the two forms seem aligned from the front view (middle), two forms from side view (right)

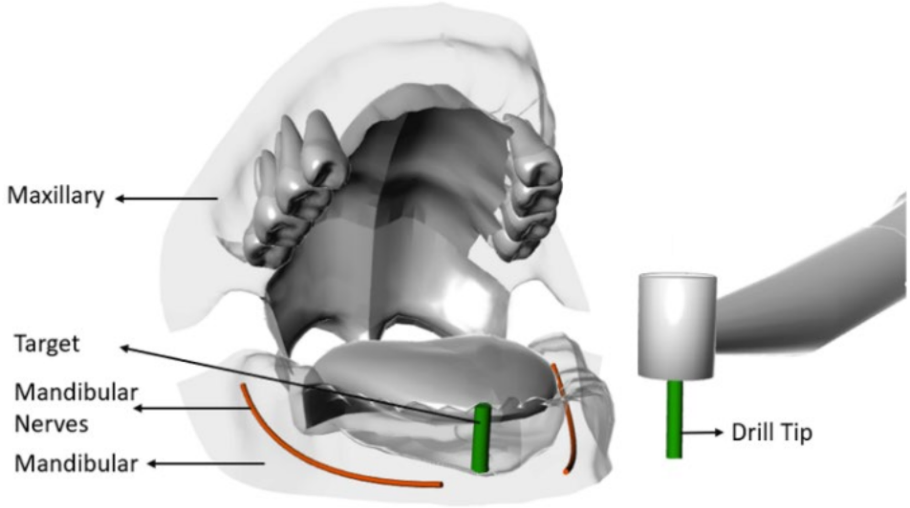

Figure 3.2: The main implantology problem: the drill must be positioned in the right position and angle in a narrow working environment without damaging tissues, bones, or nerves.

Author	**Target**	**Implant Model/ Subject**	**Number**	**AR Device**	**Frame of Reference**	**Positional Error (mm)**	**Angular Error (°)**
Ma L. et al. [2]	5x3D printed	1 Human	10	IV Overlay Device	Screen Relative	1.3	4.0
Jiang W. et al. [8]	12x3D printed	1 Phantom, 1 Human	96	3D Image Display	Screen Relative	< 1.5	< 5.5
Wang J. et al. [5]	1 Phantom	-	-	3D Image Display	Screen Relative	-	-
Katic D. et al. [6]	-	1 Pig cadaver	2	HMD	World Relative	1.1	2.0
Lin Y. et al. [4]	8x3D printed	-	48	Sony HMZ-T1	World Relative	0.5±0.3 mand., 0.5±0.2 maxillary	2.7±1.6 mand., 3.3±1.5 maxillary
Katic D. et al. [9]	2 Phantom	-	7	Sony Glasstron	World Relative	Min. 0.8, Max. 3.6	Min 1.7, Max 6.5
Ferronato et al. [1]	-	3D-printed models	2	iPad Pro 2020	Screen Relative	0.51	0.77
Song et al. [3]	-	Scaled tooth model	1	HoloLens 2	Screen Relative	3.6-32.2	2.15-45.10
Tao et al. [7]	-	Phantom	242	HoloLens 2	Screen Relative	1.31±0.67 ARN, 1.18±0.59 DSN	3.72±2.13 ARN, 3.1±1.56 DSN

Table 3.1: State-of-the-art summary in AR-assisted dental tool manipulation.

3.2 Discussion

The reviewed studies highlight the significant potential of tool manipulation widgets in enhancing the precision of dental implant surgeries. The Golden Standard Widget (GSW) was implemented through state-of-the-art analyses to compare our proposed widget to the baseline Figure 3.3. Most of the systems discussed offer promising advancements in surgical navigation, offering real-time guidance to improve the positioning of dental implants and reduce errors. However, despite these advancements, several critical limitations persist across the existing literature that warrant further discussion.

1. Static Interactions A significant limitation across many reviewed MR widget designs is the reliance on static interactions between the user and the system. In most systems, such as

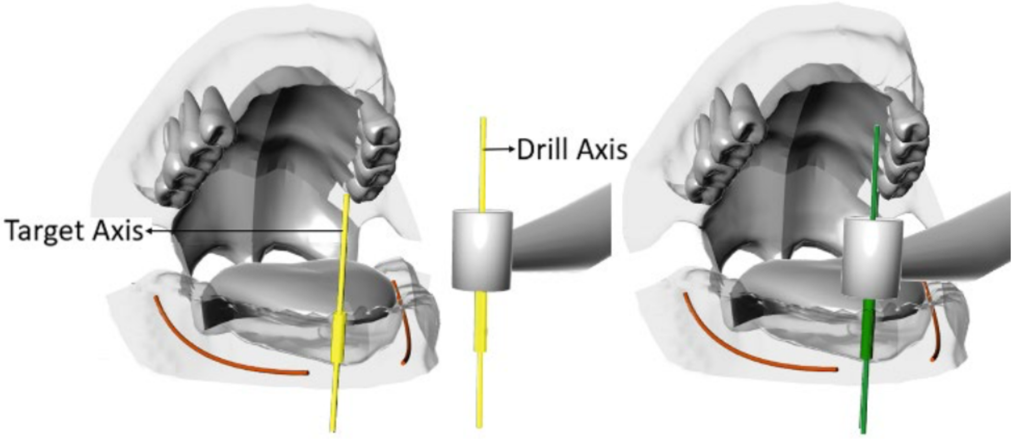

Figure 3.3: The golden standard widget (GSW): the user must align two cylinders attached to the tool and the target.

those developed by Ma et al.[2] and Song et al. [3], the user interface is primarily static, with minimal dynamic interaction that adapts to the user's actions during the procedure. For instance, many systems rely on simple overlays or static reference points without adjusting to the real-time movements of the surgical tools or adapting to changes in the surgical environment. This limits the flexibility and adaptability of the system in real-time operations,

The absence of dynamic interaction in these systems leads to potential user frustration, especially when precise tool manipulation is required. While certain MR widget designs offer visual cues, such as color-coded axes or distance indicators, these feedback mechanisms remain fixed, making it difficult for the surgeon to interact with the AR system in a way that feels intuitive and responsive to the changing conditions of the surgery.

2. Lack of User Involvement in Widget Design Another limitation across the studies reviewed is the lack of user-centered design in developing the AR system's widgets and interfaces. Few of the systems reviewed considered the user's cognitive load or involved them in the iterative design process of the AR widgets. For example, Ferronato et al. [10] and Katic et al. [6] implemented static points of interest and target axes but did not involve surgeons in the process of designing how these elements should be displayed or how they could be optimized for user interaction. This lack of collaboration with end-users—dental professionals in this case—may result in interfaces that are difficult to use, which could hinder the widespread adoption of these systems in clinical settings.

In contrast, user-centered design, where the end-user dentists are actively involved in testing, adjusting, and refining the AR interfaces, could lead to more intuitive systems better suited to real-world clinical needs. Since different users have different preferences for visual cues and interaction modalities, involving users early and continuously in the design process is crucial for developing more effective MR widget design.

3. Lack of Perception Theories in UI Evaluation One of the most notable gaps in the studies reviewed is the absence of cognitive and perception theories in evaluating the MR widget design's user interfaces. Cognitive load, visual perception, and user attention are all factors that directly influence how effectively a user can interact with an AR system during surgery. However, most of the reviewed studies—such as those by Ma et al. [2] and Song et al. [3] do not consider these aspects in their design or evaluation of the system. This oversight can lead to systems that overwhelm users with excessive or poorly designed visual information.

For instance, the lack of dynamic, context-sensitive feedback (as mentioned earlier) means that users must constantly adjust their attention to static interfaces, which may not be optimized for the real-time demands of surgery. Moreover, the visual complexity of many of these systems, with multiple overlapping elements and small-sized visual cues Figure 3.1, could lead to visual overload, increasing cognitive load and potentially decreasing the accuracy of the surgeon's decisions.

Integrating cognitive load theory and principles of visual perception into AR system design could lead to more efficient and effective user interfaces. MR widget design could better support users in high-stakes, high-concentration environments like dental surgery by reducing unnecessary visual distractions and providing more intuitive, context-aware feedback.

4. Limited Focus on Customization and Flexibility Another significant gap in the current research is the limited focus on customization and flexibility in the MR widget design. Most systems rely on uniform preset widgets and tools across different procedures and users. However, surgical procedures can vary widely depending on the individual patient's anatomy and the complexity of the procedure. For instance, Tao et al. [7] and Lin et al. [4] employ fixed AR displays that do not consider the unique needs of each surgical procedure or user. By incorporating customizable options for the visualization of the surgical area and the tools, surgeons could adjust the system's layout, colors, and types of feedback to match their personal preferences and the patient's specific needs.

5. Hardware Oriented Study Limitations The current designs of MR widget design are limited by hardware constraints, particularly the reliance on specialized head-mounted displays (HMDs) and bulky tracking devices. Studies like Song et al. [3] and Ma et al. [2] have highlighted the discomfort these devices cause, especially during long procedures. However, this research aims to study and develop next-generation interfaces that overcome these limitations.

6. Insufficient Evaluation in Real-World Settings Finally, while several studies present promising results in controlled environments (e.g., phantom or 3D-printed models), there is a lack of comprehensive evaluation of MR widget design in real-world clinical settings. For instance, Katic et al. [6] and Lin et al. [4] evaluated their systems in cadaver models or controlled environments, but the complexities of real-world surgery, with its unpredictability and variability, may present additional challenges not accounted for in these studies. There is a clear need for further research involving larger-scale, real-world clinical trials to assess these MR widget designs' true effectiveness and reliability under actual surgical conditions.

3.3 Chapter Conclusion

While the studies reviewed highlight the promising potential of augmented drill tool manipulation widgets in improving precision and reducing errors of tool manipulation in dental surgeries, the lack of dynamic interaction, user involvement in widget design, and the absence of perceptual theory-based UI evaluations represent significant limitations that need to be addressed in future research. Moreover, the current systems' reliance on static UI elements and the ergonomic discomfort caused by bulky hardware may hinder their widespread adoption. Future advancements of these widgets should prioritize user-centered design, cognitive load reduction, and customization options to enhance usability and performance. By addressing these gaps, MR dental drill tool manipulation widgets can offer more effective and adaptable solutions, improving surgical outcomes, task load, and user acceptance.

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Part 4: Methodology

Gestalt Theory of Perception

In the previous chapters, **Chapter 2** and **Chapter 3**, we explored existing tool-to-target manipulation widgets in various fields, particularly in dental applications, and identified key challenges in widget design and usability. In contrast to existing literature reviewed, this thesis introduces a novel methodology that integrates preattentive perception techniques, informed by the principles of Gestalt theory [1], [2], to design more intuitive and efficient spatial interfaces specifically for dental tool manipulation case studies. Preattentive perception refers to the brain's capacity to immediately and effortlessly process certain visual features, allowing for rapid recognition of essential elements in a scene without conscious thought. This perceptual ability is especially valuable in high-stakes environments, such as surgery, where quick decision-making is crucial.

In this study, we leverage Gestalt principles to enhance the design of MR widgets, aiming to improve how users perceive, interpret, and interact with spatial-augmented interfaces during dental procedures. Gestalt theory emphasizes the human tendency to perceive complex scenes as organized wholes and provides valuable insights into structuring visual information that aligns with natural cognitive processing [3]. A key aspect of our approach is the integration of these principles with the precision mechanics of dental tools. By optimizing both the visual representation and physical manipulation of surgical instruments, we ensure that the interface communicates critical tool-related information that aligns with preattentive perceptual processes [4].

Specifically, we incorporate the following Gestalt principles Figure 3.4 into our widget design methodology:

Proximity: Objects placed close together are perceived as related. We apply this principle by visually grouping related elements—such as surgical instruments and their target areas—to guide the surgeon's attention to the most pertinent information. This spatial arrangement facilitates rapid recognition of tool relationships and enhances the cognitive mapping of tool placement during procedures.

Similarity: Visual elements that share common characteristics are perceived as part of a group. We implement this principle by ensuring consistent visual presentation of similar data types, such as depth cues or alignment indicators. By using uniform visual markers—such as color or shape—for different data categories, we simplify the cognitive processing of the AR interface, allowing the surgeon to interpret the scene.

Continuity: The human brain tends to follow continuous lines or patterns. To leverage this principle, we design smooth, continuous visual trajectories in the AR interface that guide the surgeon's eye along the tool path. This enhances spatial awareness, ensuring the surgeon can accurately track tool movement relative to the target area.

Closure: The mind fills in missing elements to complete familiar shapes or objects. By applying this principle, we ensure that even partial visual cues—such as incomplete outlines or segmented tool trajectories—are sufficient for the surgeon to infer missing information. This

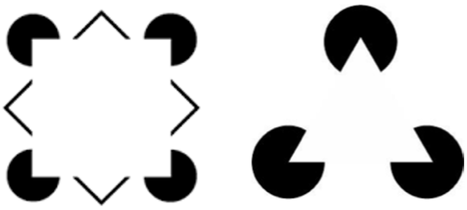

Figure 3.4: Gestalt Reification principle: the mind visualizes a white cube (left) and a triangle (right) in a quick, pre-attentive way.

capability minimizes cognitive load and facilitates quicker, more intuitive decision-making during complex dental procedures.

In addition to these Gestalt principles, we incorporate a sophisticated collimation mechanism for mechanical tool manipulation. The collimation process ensures that the mechanical tool's movements are precisely aligned with the AR interface, maintaining spatial coherence between the tool's position and its visual representation. This alignment is crucial in high-precision tasks such as dental surgeries, where minute adjustments can significantly affect patient outcomes.

By applying Gestalt principles and mechanical tool collimation, we aim to create AR interfaces that support surgeons in performing highly precise tasks with minimal cognitive effort. These interfaces reduce the cognitive load on the surgeon and provide real-time feedback that aligns with the natural flow of decision-making during surgery. This approach is particularly relevant in dental surgeries, where precision and speed are paramount.

Building on the insights gained from Gestalt theory, the subsequent stages of this design process involved exploring how these principles could be practically applied to enhance tool-positioning tasks in the step MR widget development. The next sections of the thesis will discuss how these widgets were implemented and evaluated through objective and subjective measures. These evaluations bridge the theoretical understanding of perception and the practical application of MR technology in the dental and medical fields, ultimately improving patient safety and surgical outcomes.

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Chapter 4

Virtual Stigmometer Widget (ViSti)

Chapter Summary

Building upon the previous chapter's insights, the current chapter introduces the Virtual Stigmometer Widget (ViSti), a novel mixed reality (MR) tool to enhance the precision of dental drill positioning. This chapter explores the design, implementation, and evaluation of the ViSti widget, focusing on how it reduces task load during tool positioning. Additionally, the results from a user study comparing ViSti with traditional methods further validate its effectiveness. The findings contribute to advancing the understanding of how MR-based widgets can improve precision tool guidance in specialized fields such as dentistry.

In dental tool positioning, precision is critical, particularly for the accurate alignment of drills. Even a minor error can have significant consequences, such as nerve or bone damage. While previous research has demonstrated the potential of assistive tools in positioning tasks, existing widgets typically rely on static, quasi-static, or simple 3D graphical cues, which may not provide the precision required in high-stakes settings like dental surgeries. In response to these limitations, we developed the ViSti, a dynamic MR tool that visually indicates the magnitude of positioning errors by subtly blurring the view, gradually focusing as the tool approaches the target (implant drilling location), and achieving perfect alignment (collimation) when precise placement is reached.

We conducted a within-subject experiment with 30 participants to validate its effectiveness, comparing the ViSti widget against the traditional "gold standard" method across 32 positioning tasks. The results, as measured by the NASA-TLX survey, revealed that the ViSti significantly reduces frustration (-43%), mental demand (-19%), and enhances perceived performance (+8%). However, as expected, there were trade-offs: ViSti resulted in increased effort (+34%), physical demand (+33%), and temporal demand (+4%). Despite these trade-offs, the ViSti widget demonstrated significant potential for use in dentistry and other industries requiring 5 dof precision.

Contents

4.1 Widget Design

We applied photographic focus to the implementation of our widget design. The concept is to create a visual condition for our widget, the Virtual Stigmometer Widget. The objective is to convey tool positioning and rotation information with a rapid glance and without obstructing the dentist's point of view.

The word stigmometer derives from “stigma” (in Greek) and stands for “point.” In ophthalmology, the derivative astigmatism is commonly used for sight imperfection of the eye where the vision is blurry at all distances. In photography, where the focus is the key factor for the cameras for high-quality photos, the stigmometer mechanism provides a split-image rangefinder that simulates the way the photographer visualizes the out-of-focus situation by splitting the view Figure 4.2 and Figure 4.3.

Technically, stigmometer lenses can create blurred and split vision in the viewfinder thanks to two micro prisms placed in the camera that are opposed. The photographer ensures the focus

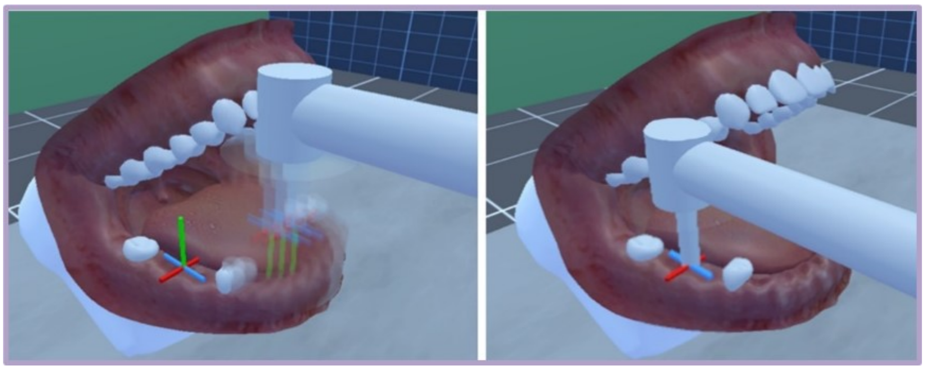

Figure 4.1: Innovative Virtual Stigmometer Widget (ViSti) supports precise 5DOF Dental Drill Tool Positioning: The drill tool out of the target is blurred (left), and the drill tool on the target is focused (right).

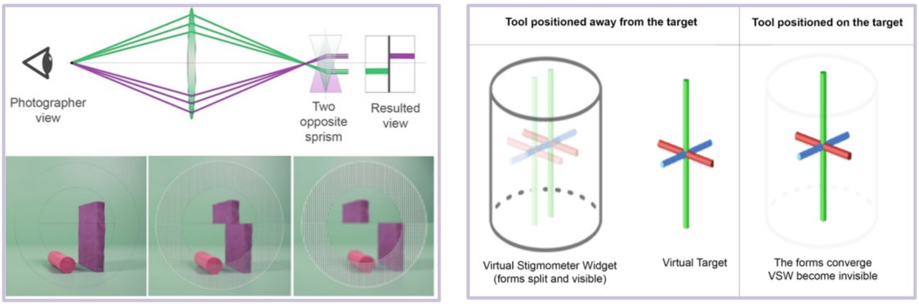

Figure 4.2: The stigmometer viewfinder (left image): The two opposite prism lens mechanism (left-up), the representation of the stigmometer viewfinder in analog cameras from left to right; focused view to split view viewfinder image (left-down), The Stigmometer Widget on (right).

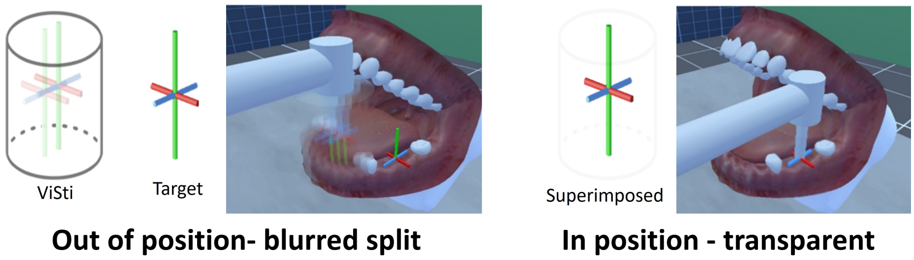

Figure 4.3: The stigmometer viewfinder mechanism.

or out-of-focus situation with a rapid glance by finding the correct range through the viewfinder. If the vision is clear, the subject is focused; meanwhile, when the image is jagged and split, the subject is out of focus. The vision's segments are misaligned from one another. Although this focusing mechanism is manual, it does not destroy the point of view, and it is simple, intuitive, and fast. It indicates out-of-focus conditions with a rapid glance at the photographer.

Secondly, it enables tool positioning accurately on the implant target with less cognitive demand and natural interactions. Further, ViSti can effectively divert the user's attention to the surgical area. Even though AR surgery has not been fully implemented in dental implant surgeries, the ViSti mechanism can allow precise focus results that distinguish minor details.

We aim to allow users to align the tool with the target and avoid complex interactions and visual intensity. The 3D AR lenses have challenges in implementing depth perception cues or physical constraints [1], [2]. We initially designed our stigmometer widget lens prototype as a 2D flat form. However, this idea was discarded since the mouth is a small workplace, and ViSti should be considered in that context. Later, we implemented ViSti using primitive 3D forms such as cubes, spheres, and cylinders.

We implemented ViSti as a Unity shader to demonstrate the error visual amplification. We initially applied it in 2D form but later implemented it on a 3D cylinder. This aspect also simulates the dentist's zoom lenses in the surgical area. We set the following error threshold: 2mm/ 50 mm for the positional error and 2°/45° for the angular error; the ViSti dynamically appears around these parameters. The characteristics of the five visual assets (e.g., transparency, size, color) are compatible with other headset devices, such as HoloLens 2. The ViSti assists the dentist in positioning & aligning the drill tool in the correct place. The drill tool positioning task might be intuitive, as well as the stigmometer mechanism. It allows for comparing and analyzing the subject's proximity, length, and angle orientations with its context relationship. If the drill tool is in the correct destination place and angle, the stigmometer form is focused, and the vision is clear. If the drill tool is displaced and misaligned, the stigmometer form is out of focus, and the vision is blurred Figure 4.1.

4.2 Evaluation

A within-subjects user study was conducted to evaluate the performance of the ViSti compared with the GSW widget described in 3. To ensure consistency and reproducibility in line with established methodologies. Participants provided informed consent before the study. Before engaging in the main task (mandibular scene), a training scene was provided to allow participants to familiarize themselves with both widgets.

We opted for AR simulation in VR for this preliminary evaluation as it offers several advantages: it enables iterative design in a controlled setting, is free from tracking issues, and ensures a safe, risk-free testing environment. While this approach is ideal for our current study, the widget design is highly adaptable and can easily transition to next-generation mixed reality (MR) interfaces, which will benefit from enhanced tracking capabilities in the future.

4.2.1 Metrics and Hypotheses

Quantitative metrics were collected during the experiment, while qualitative evaluations were made using the NASA TLX scale, which assessed the following dimensions: Mental Demand, Physical Demand, Temporal Demand, Perceived Performance, Effort, and Frustration. These were rated on a Likert Scale (LS) from 1 to 7. Additionally, participants were asked to indicate their preferred widget on the same scale.

We evaluated the following seven hypotheses through the experiment:

- H1: ViSti has less mental demand.
- H2: ViSti has less physical demand.
- H3: ViSti has less temporal demand.
- H4: ViSti has better perceived performance.
- H5: ViSti requires less effort.
- H6: ViSti results in less frustration.
- H7: ViSti is the preferred widget.

4.2.2 Participants

A total of 30 participants were recruited for the user study, consisting of 15 engineering students and 15 medical students. The demographic breakdown was as follows: 55% male, 45% female, and ages ranging from 20 to 35 years (mean age = 26, standard deviation = 3.92). Out of the 30 participants, 26 were right-handed. Additionally, 5 participants were AR/VR app developers, 15 had used VR/AR applications at least once, and 10 were novices in AR/VR technologies.

4.2.3 Setup and Procedure

The experiment was conducted in a simulated dental environment using Unity, and a standalone application was developed for the Oculus Quest 2. The dual-touch controllers of the Oculus Quest

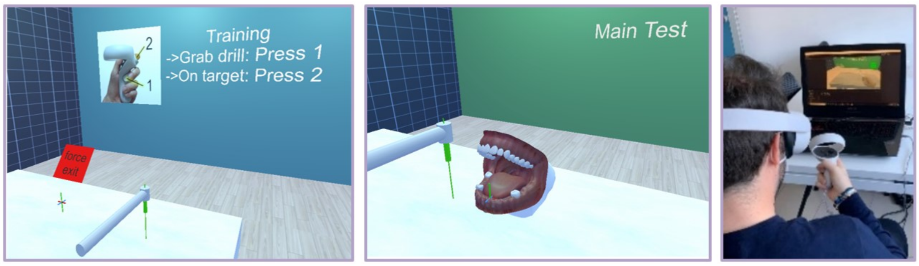

Figure 4.4: VR setup of GSW training (left), main test (middle), and experiment setup (right).

2 were utilized for interaction, with the grip button controlling the drill tool and the trigger button confirming target positions. The training scene included a 12m^2 room with a table and 16 random targets arranged in a 0.3m diameter sphere centered on the initial tool position. Participants performed 16 positioning tasks (8 with each widget). The main test scene involved the mandibular area of a virtual patient, with 32 targets arranged on the avatar's mouth. Participants performed 32 positioning tasks (16 with each widget).

The experiment was divided into two treatments, each targeting the mandibular area. The targets were presented randomly, and each appeared only once during the experiment. The participants were instructed to focus on precision rather than task completion time and were prohibited from using the desk as an armrest or emulating the dentist's actual working conditions.

Before the experiment, participants were shown an introductory video explaining the objectives, the procedure, and how both widgets function. After giving informed consent, participants were seated on a dental stool, wore the Oculus Quest 2 headset, and adjusted themselves in the virtual environment.

Participants interacted with targets in the virtual room during the training session. These targets were then moved to the mandible for the main session. Once the participant confirmed the final positioning, the next scene loaded automatically. In case of any extreme circumstances or the need to pause the experiment, the participant could do so. An observer was present throughout the experiment to supervise and record any unusual events.

4.3 Results

The experiment's training and main sessions were conducted without any anomalies or interruptions, with an average test duration of 30 minutes. We analyzed a total of thirty NASA-TLX responses. According to the results shown in Figure 4.4, ViSti outperformed GSW in terms of user experience, as it resulted in lower frustration (LS 2.07/7 vs. 2.97/7, -43%) and reduced mental demand (LS 2.63/7 vs. 3.13/7, -19%). Additionally, participants reported a better-perceived performance with ViSti (LS 4.30/7 vs. 4.67/7, +8%).

Based on the analysis, the null hypothesis for normality was rejected, and the results from the Mann-Whitney U one-tailed test revealed significant differences between the two treatments. Specifically, ViSti required less user effort ($W = 177.00$, $p < .001$) and physical demand ($W = 199.50$, $p < .001$). However, ViSti exhibited higher levels of effort (LS 4.13/7 vs. 2.73/7, +34%), physical demand (LS 4.17/7 vs. 2.77/7, +33%), and temporal demand (LS 2.77/7 vs. 2.80/7, +4%). These results align with the expected outcome, suggesting that users position the tool in a way that avoids haptic feedback for unsupported limbs in the air.

Hypotheses H1, H4, and H6 support that our widget results in lower mental and temporal demand, less frustration, and better-perceived performance. These findings indicate that ViSti's design is more supportive than GSW's. A total of 12 out of 30 participants (40%) preferred ViSti. One participant mentioned that the tool positioning task with ViSti was easier, as it did not create visual clutter on the mouth and facilitated better alignment of thin target cylinders.

On the other hand, hypotheses H2, H3, and H5 do not support the claim that ViSti requires more physical demand, temporal demand, and effort. Three participants reported challenges with ViSti during the learning phase; however, as the study progressed, they adapted to the widget and

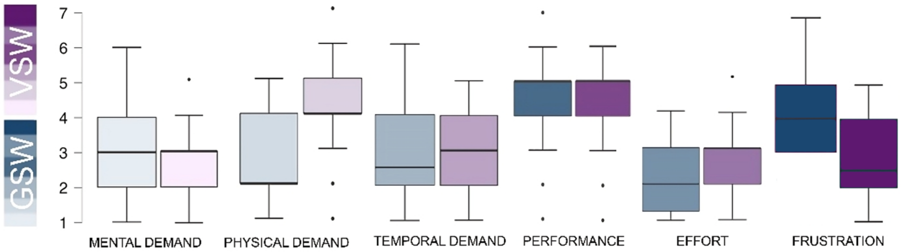

Figure 4.5: Boxplot of NASA-TLX, ViSti over GSW.

saw efficiency improvements, particularly in the time required for the tool positioning task, as shown in Figure 4.5.

4.4 Chapter Conclusion

In this chapter, we presented the implementation and evaluation of the ViSti vs golden standards, an innovative interactive 5DOF tool positioning widget designed for dental implantology applications. The ViSti widget was developed and tested using the Unity engine, demonstrating both adequacy and flexibility across various configurations, allowing for continuous refinement and enhancement. The NASA-TLX results revealed that ViSti significantly outperformed the golden standard widgets regarding frustration, mental demand, and users' perceived performance. These findings highlight the effectiveness of the ViSti widget in improving user experience and interaction in complex tasks.

The design of ViSti promises preattentive interaction, enabling users to perform tool manipulation tasks while maintaining the unobstructed perception of their environment. This approach has strong implications for the future of UI design, particularly for next-generation AR glasses with enhanced tracking capabilities, where platform independence is critical. We focused on evaluating user performance and acceptance rather than being confined to specific hardware or software solutions.

Despite its success, there are some limitations in the current implementation. Challenges arose when the 2D photography mechanism was translated into a 3D environment, suggesting that there is still room for refinement. Additionally, certain AR-related issues, such as hand occlusion, may present challenges that were not fully replicated in the VR simulation, which could affect the generalizability of the results. Moreover, it is important to note that while we assessed subjective task load using the NASA-TLX, we did not measure quantitative metrics such as task completion time or accuracy, which could provide additional insights into the widget's performance. Therefore, for the next chapter, we aim to draw inspiration from the ViSti widget and explore different configurations of gain functions (e.g., nonlinear) and parameters to optimize the widget further.

References

[1] Li, G., Lee, D., Jeong, Y., Cho, J., and Lee, B., "Holographic display for see-through augmented reality using mirror-lens holographic optical element," *Optics letters*, vol. 41, no. 11, pp. 2486–2489, 2016. DOI: 10.1364/OL.41.002486.

[2] Looser, J., Grasset, R., and Billinghurst, M., "A 3d flexible and tangible magic lens in augmented reality," in *2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality*, IEEE, 2007, pp. 51–54. DOI: 10.1109/ISMAR.2007.4538825.

Chapter 5

Augmented Collimator Widget (ACW)

Chapter Summary

In previous **Chapter 4**, we explored the Virtual Stigmometer Widget (ViSti) and demonstrated its effectiveness in improving task load during dental drill positioning. However, no precision parameters were compared with Golden Standards; therefore, building upon this previous work, **Chapter 5** introduces the Gestalt Driven Augmented Collimator Widget. This new widget applies Gestalt principles of perception to address the challenge of visual clutter and occlusion in tool-positioning systems. In this chapter, we will discuss how Gestalt theory informs the widget's design and enhances user performance in 3D spatial environments. User study results will be presented to evaluate the Gestalt Driven Widget's ability to improve tool alignment precision compared to existing methods, marking a significant advancement in MR-assisted precision guidance.

Drill tool positioning in dental implantology is a challenging task requiring 5DOF precision as the rotation around the tool axis is not influential. This work improves the quasi-static visual elements of the state-of-the-art with a novel Augmented Collimation Widget (ACW), an interactive tool of position and angle error visualization based on the gestalt reification, the human ability to group geometric elements. The user can seek in a quick, pre-attentive way the collimation of five (three positional and two rotational) error component widgets (ECWs), taking advantage of three key aspects: component separation and reification, error visual amplification, and dynamic hiding of the collimated components. We compared the ACW with the golden standard in a within-subjects (N=30) user test using 32 implant targets, measuring the time, error, and usability. ACW performed significantly better in positional (+19%) and angular (+47%) precision accuracy and with less mental demand (-6%) and frustration (-13%), but with an expected increase in task time (+59%) and physical demand (+64%). The interview indicated that ACW is the main preference and is aesthetically more pleasant than GSW, proposing it as the new golden standard for implantology and for other applications where 5DOF positioning is key.

Contents

5.1 Widget Design

The design objective of the ACW is to visualize the positional (pe, vector) and angular error (ae, quaternion) of the tool in a quick and preattentive way compared to the designated target. ACW is virtually attached to the drill tool in the user's hand for leveraging proprioception [1]. In a preliminary exploration of the Gestalt theories, we quickly implemented and tested several concepts Figure 5.2, and learning from mistakes, we refined the final design which integrates the three key aspects.

5.1.1 Error Components' Separation and Reification

ACW breaks down the 5DOF error visualization in spatial components. This approach is common in literature [2] and desktop 3D CAD systems, as it reduces cognitive and coordination effort and can improve precision and usability. Positional (pe) and angular (ae) errors are defined as,

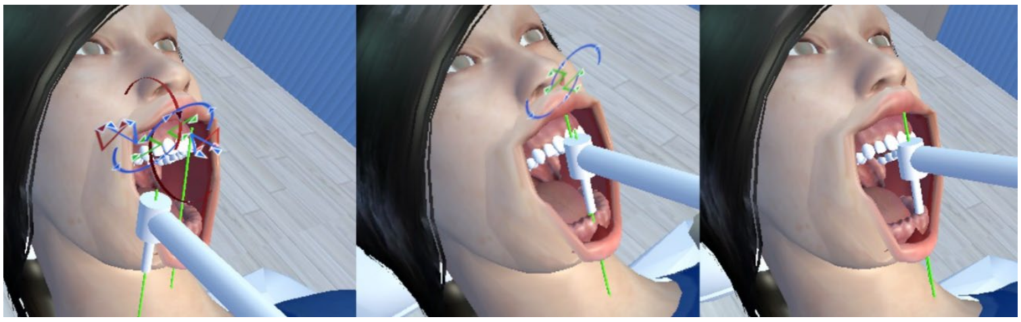

Figure 5.1: Our novel Augmented Collimator Widget (ACW) supports precise 5DOF drill tool positioning in dental implantology. ACW leverages the Gestalt principles, component separation and reification, error visual amplification, and dynamic hiding: approach (left), partial collimation (center), and full collimation, ACW disappears as not needed (right).

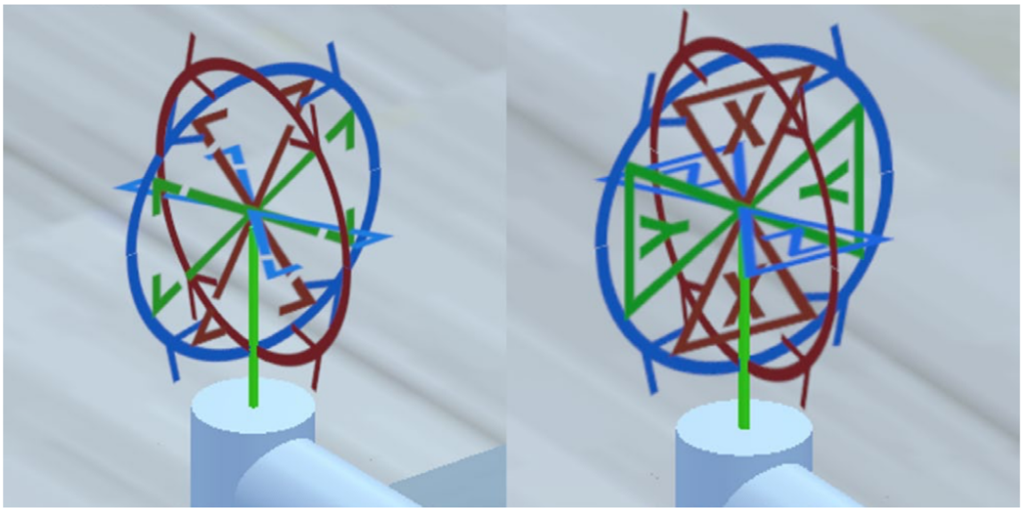

Figure 5.2: Two (of the many) discarded ACW prototypes resulted in visually occluded, complex, or not easy to use.

$$\mathrm{pe} = \mathrm{dp} - \mathrm{tp} \tag{5.1}$$

where dp and tp are the positional vectors in world space, respectively, of the drill tip and the implant target entry point designed from preoperative;

$$\mathrm{ae} = \mathrm{dq} \times \mathrm{tq}^{-1} \tag{5.2}$$

dq and tq are the quaternions, respectively, of the drill tip and the implant target directions.

We used five -conceptually similar- world-referenced error component widgets (ECW): three for the positional, PEXW (horizontal, positive towards the right side of the user initial position), PEYW (positive up), PEZW (positive front), and two for angular AEXW (pitch), and AEZW (roll).

Each ECW is quickly identified by a pair of facing symbols laid on the same plane and moving symmetrically along the component direction or axis: ">" for positional and "C" for angular error and color (red, green, and blue). The ECW symbols are chosen to convey strong reification when collimated along a component: position collimation forms an equally colored "X" and angular a full circle. The ECW collimation indicated a perfect positioning of that component. After initial tests, we added some small arrows to the original symbols to have a quick hint of the direction associated with the specific ECW.

The five ECWs (all together compose the ACW) are arranged in the space according to their spatial meaning and scaled to be all visible before and during the collimation (Fig. 6).

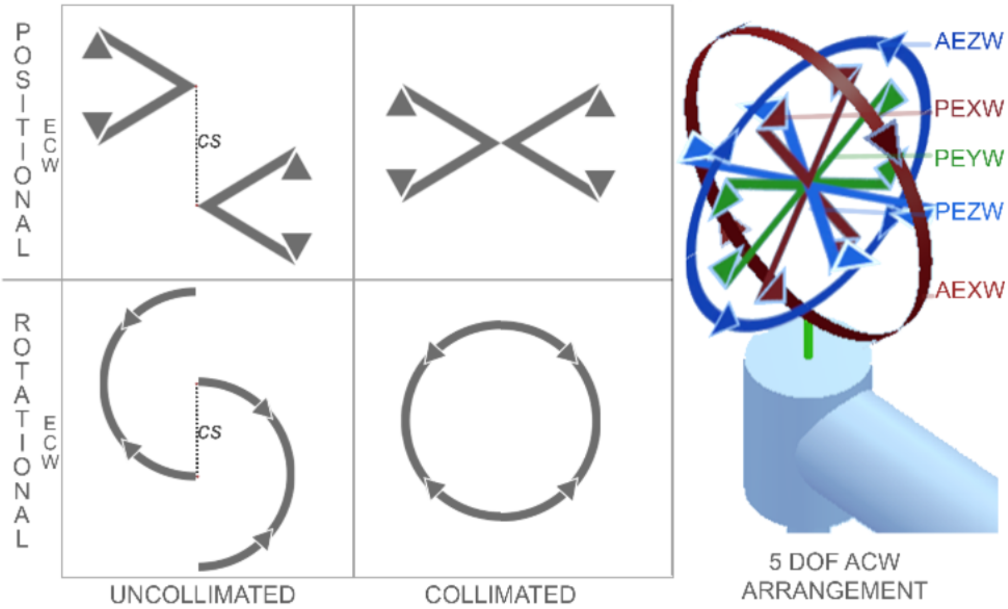

Figure 5.3: The error component widget (ECW) - before (left) and after (center) collimation- and a fully collimated ACW with all five ECWs assembled in 3D space (right).

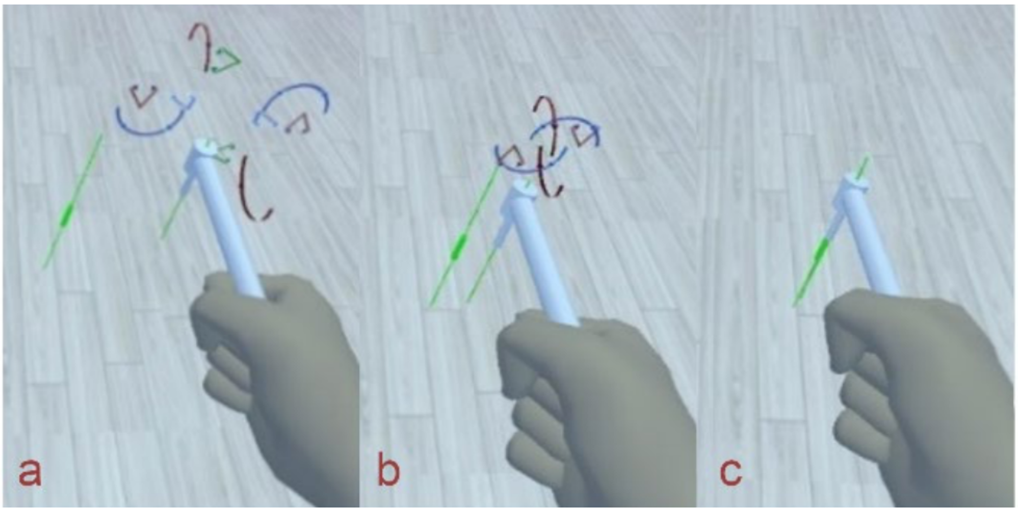

Figure 5.4: ACW dynamic hiding: all 5 ECWs are uncollimated and visible (a), PEYW and PEZW disappear (b), and the target is fully acquired (c).

5.1.2 Error Visual Amplification

This aspect mimics common dentists' practice of using zoom lenses. We used visual amplification of the ECW error response to overcome the physical resolution of the AR display and the limited human capability to perceive the error. We define the collimator separation (*csi*) as the linear distance in the virtual world space of each ECW (*i*) symbol pair Figure 5.3. We implemented a piecewise function (3) to amplify the visual for each ECW*i* where Gaini is the linear amplification factor, and *ei* is the scalar value of the specific ECW*i* (distance or Euler angle). A positive gain will amplify the error visualization as seen by the user during the collimation Figure 5.5.

In early tests, we observed that when the drill was far from the target (e.g., approach phase), the cs was large, and the widget was invisible because the two halves were out of the user's sight frustum. Therefore, we implemented for each ECW a *mdti*. This max distance threshold clamps the amplification at larger error values, where the visual approach is sufficient and even more effective than ACW. Similarly, we clamp the amplification to 0 when the *accei*, the accepted error,

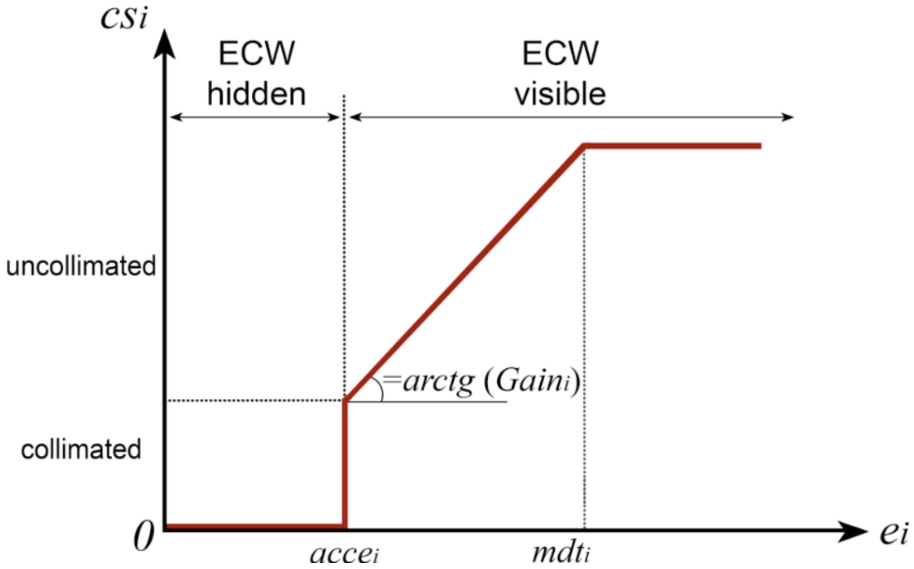

Figure 5.5: ECW visual amplification behavior (*csi*) with the error (*ei*).

is reached to avoid the user's struggle to seek an unnecessary and impossible-to-reach ideal value.

5.1.3 Dynamic Hiding of the Collimated Components

In early designs, we observed that the ACW widget becomes visually crowded and complex to understand in near-collimation conditions. To address this issue, we first located ACW on the top of the tool for better visibility of the working area, a safety measure not considered in previous works. In addition, we reduced the user's visual and cognitive effort by hiding the ECWs below the accepted error *accei*. In practice, the user, after initial training, will use his pre-attentive skills to make all the ECW collimate and disappear Figure 5.4).

5.1.4 ACW Implementation

We implemented the ACW with a modular approach, designing a unique Unity 3D ECW prefab. When the user grabs the drill and moves it in space at runtime, the main script triggers a tool "position modified," which includes the positional and angular error components compared to the current target position Figure 5.1. Each ACW's five ECW prefab is instantiated with a different texture, spatial orientation, and behavior parameters (Gaini, *accei*, *mdti*) and is connected to the related components. This approach allowed us in the initial phase to try and evaluate different visual configurations and behaviors in a short time in a heuristic way to find the optimal final design used in the experiment.

5.2 Evaluation

We conducted a within-subjects experiment to compare ACW to GSW 3 like in the previous chapter; however, this chapter focused on comparing both quantitative and qualitative metrics from the new user study to assess the performance of this newly implemented widget. We chose to simulate AR simulation in VR because of the COVID-19 pandemic limitations and to obtain a consistent and repeatable setup as reported in the literature [3]. The study has complied with the American Psychological Association Code of Ethics, and informed consent was obtained from each participant. We set five hypotheses:

H1. ACW improves positional precision and accuracy vs GSW; **H2.** ACW improves angular precision and accuracy vs GSW; **H3.** ACW reduces execution time vs GSW; **H4.** ACW reduces the mental load vs GSW; **H5.** ACW improves perceived performance vs. GSW.

Figure 5.6: The experiment welcome room: instructions are displayed on the front wall. The user interacts with the drill tool using the dominant-hand controller and the non-dominant hand to interact with the 3D menu buttons.

5.2.1 Participants

Thirty unpaid voluntary subjects (n=30) were recruited from a local university from 21 engineering and nine medicine students (33.3% male and 66.7% Female), aged between 21 to 34 Years (27 average and 3,188 standard deviations), 90% are right-handed, and 10% are left-handed, and 3 participants develop AR/VR applications, 15 novice AR/VR users.

5.2.2 Setup

Users sit on a stool like a dentist's practice in front of a table. The VR system is the Oculus Quest 2 with dual touch controllers. The dominant hand controller grip button is used to grab the drill tool, and the trigger button is used to confirm the target position. The non-dominant controller has a ray cast that interacts with the 3D menus with the trigger button. We developed a standalone application on the Oculus using Unity 3D to perform the test procedure Figure 5.6, with a welcome room with visual instructions and 3D buttons to select one of the two treatments. We created a training scene composed of a 4mx3m room with a table and 32 random targets in a sphere of a 30 cm radius centered on the initial tool position. The test scene is composed of an identical room. Still, instead of the table, it shows a static patient avatar with a mouth open and 32 target sets (one for each tooth, 16 maxilla, and 16 mandibular) positioned by an experienced dentist. The application in both scenes displays all the targets randomly and once simultaneously. Graphical elements transparency was set to be visually equivalent to a HoloLens 2 display. When the user is confident of the positioning, the user hits the trigger button, and the app saves the captured metrics in a comma-separated file.

We set the following ACW parameters:

$$accei = 2\,\text{mm}, \quad mdti = 50\,\text{mm}, \quad \text{Gain} = 50\,\text{for positional ECWs}$$

$$accei = 2^\circ, \quad mdti = 45^\circ, \quad \text{Gain} = 0.1\,\text{for angular ECWs}$$

5.2.3 Procedure

Each participant receives a preliminary introduction outlining the test objectives and procedures, provides consent, and confirms the absence of any general discomfort, fatigue, eye strain, difficulty focusing, or headaches before the experiment begins. The participant then watches an introductory video explaining the functionality of the two widgets and the interface of the experimental application.

Following this, the participant is seated on a dentist-style footstool, wears the Oculus Quest 2 headset, familiarizes themselves with the virtual reality environment and controls, and selects a designated treatment set according to a Latin square order:

- A: GSW training, ACW training, Mandibular (MD) GSW, Maxillary (MX) GSW, Mandibular (MD) ACW, Maxillary (MX) ACW;
- B: ACW training, GSW training, MD-ACW, MD-GSW, MX-ACW, MX-GSW.

During the training session, targets are located in the space, while in the other sessions, the targets' locations vary between the mandible and maxillary regions. Participants are not allowed to use the desk for arm support, mimicking real-life dental conditions, and are instructed to prioritize maximum drill precision over task completion time. Once one treatment is completed, the application automatically loads the next task in the set.

After completing the task, the participant removes the headset and is asked to fill out an online questionnaire. We implemented all health and hygiene protocols using disposable masks and sanitizing devices,and cleaning procedures for all surfaces.

5.2.4 Metrics

We acquired the following metrics using the test application:

- **Positional Error Magnitude** (*pem*): Scalar value in millimeters.
- **Positional Error Components** (pex/y/z): Cartesian world-referenced components of positional error.
- **Angular Error Magnitude** (aem): Rotation angle in degrees.
- **Angular Error Components** (aex/y/z): Rotation angle components in degrees.
- **Task Time** (tt): Time elapsed between the new target display and the user button press, measured in milliseconds.

For the qualitative evaluation of the user experience, we gathered the following data: NASA TLX (Mental, Physical, and Temporal Demand) [4], Perceived Performance Rate (Likert 7-point scale), Aesthetic Rating (Likert 7-point scale), and Preferred Widget (Likert 7-point scale).

5.3 Results

All participants performed both the training and experiment sessions without interruptions or anomalies. The average time for the test (excluding training) was 6.10±4.13 minutes. We analyzed a total of 1920 observations (30 × 2 × 32) for outliers. We removed the first target data of each treatment (30 × 2 × 2) from each participant's data, as the assistant notes and statistical analysis revealed significant differences in time and precision compared to subsequent targets. This anomaly can be attributed to the user interacting with the "next treatment" button or the drill grab required at every treatment change. The remaining 1800 entries (30 × 2 × 30) were analyzed.

5.3.1 Positional Error

The descriptive statistics show similar skewed behavior for both treatments, supported by the rejection of Shapiro-Wilk's test of normality and the Equality of Two Variances (Levene's). Therefore, we apply the nonparametric independent Mann-Whitney U one-tail test, which indicates that ACW is significantly more precise and accurate (2.24±1.42 mm for ACW and 2.72±2.75 mm for GSW) than GSW (W = 331360.000, p< .001) Figure 5.7.

Upon studying the positional error components (pex-y-z), we can see that all components reject the null hypothesis for normality, and the Mann-Whitney U one-tail test finds that pex and pez differ significantly between the two groups.

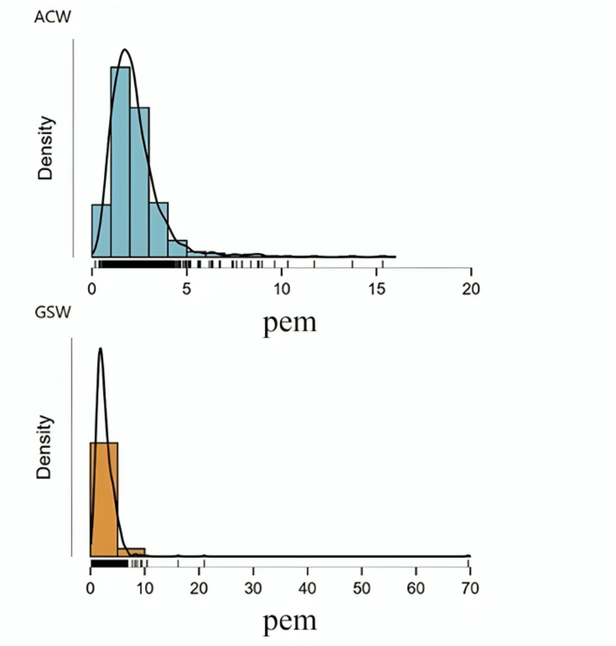

Figure 5.7: Distribution Plots for positional error magnitude (*pem*).

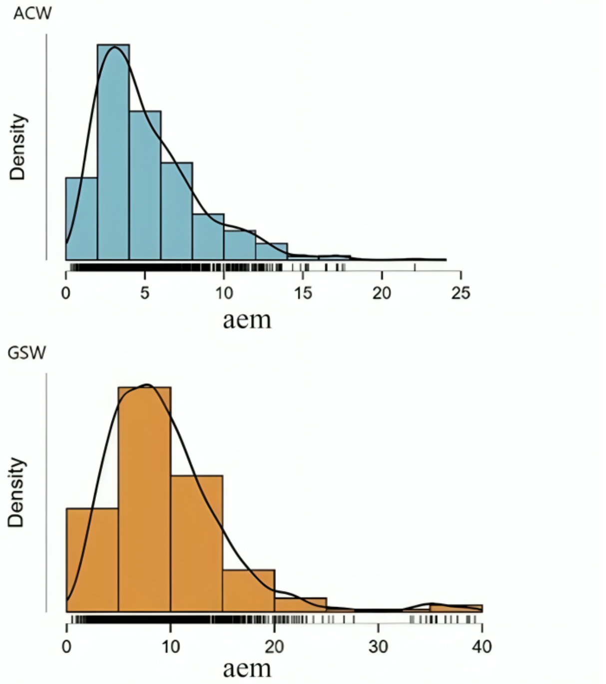

Figure 5.8: Distribution Plots for Angular Error Magnitude (aem)

5.3.2 Angular Error

The descriptive statistics show similar skewed behavior in both groups, with a sample mean of 5.03±3.13° for ACW and 9.54±5.77° for GSW. Shapiro-Wilk's and Levene's tests are not rejected, indicating that the data might not be normally distributed and that the variances are unequal. Therefore, we apply a nonparametric independent one-tail Mann-Whitney U test, which indicates that ACW is significantly more precise and accurate than GSW (W=178363.500, p< .001) Figure 5.8. The box plot results also show that the mandibular condition is more precise than the maxillary condition Figure 5.9.

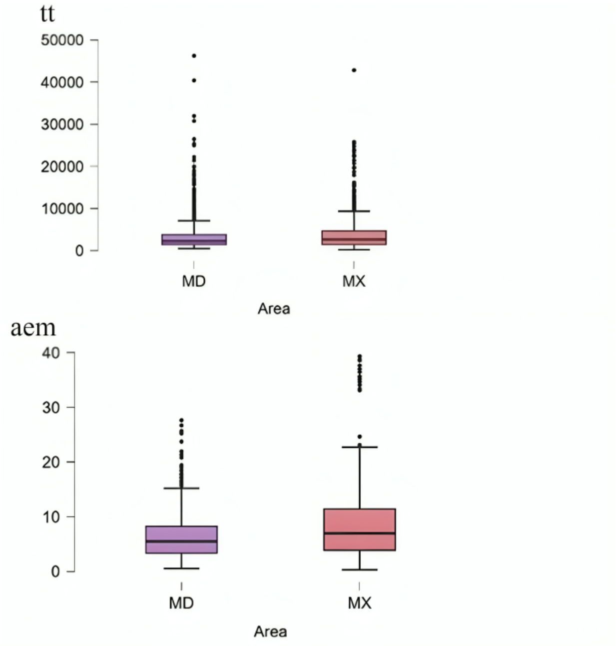

Figure 5.9: Box Plots of tt and aem for Mandibular (MD) and Maxillary (MX)

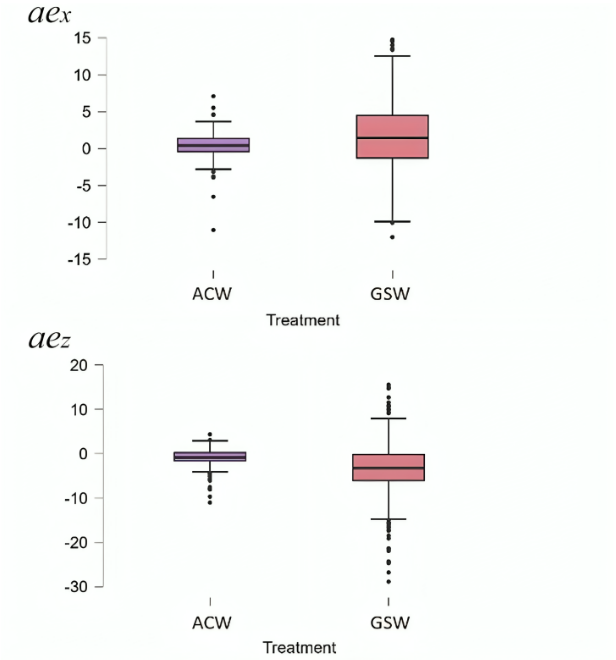

Figure 5.10: Box plots for aex and aez components.

Upon studying the angular error components (aex-y-z), we observe that all components reject the null hypothesis for normality. The Mann-Whitney U one-tail test finds that gender and aez differ significantly between the two groups Figure 5.10.

5.3.3 Task Time

The descriptive statistics (Table 4) show similar skewed behavior in both treatments, with a sample mean of 5194.4±4918.579 milliseconds for ACW and 2141.882±1817.623 milliseconds for GSW. Shapiro-Wilk's and Levene's tests are not rejected, indicating that the data might not be normally distributed and that variances are unequal. Therefore, we apply the nonparametric independent

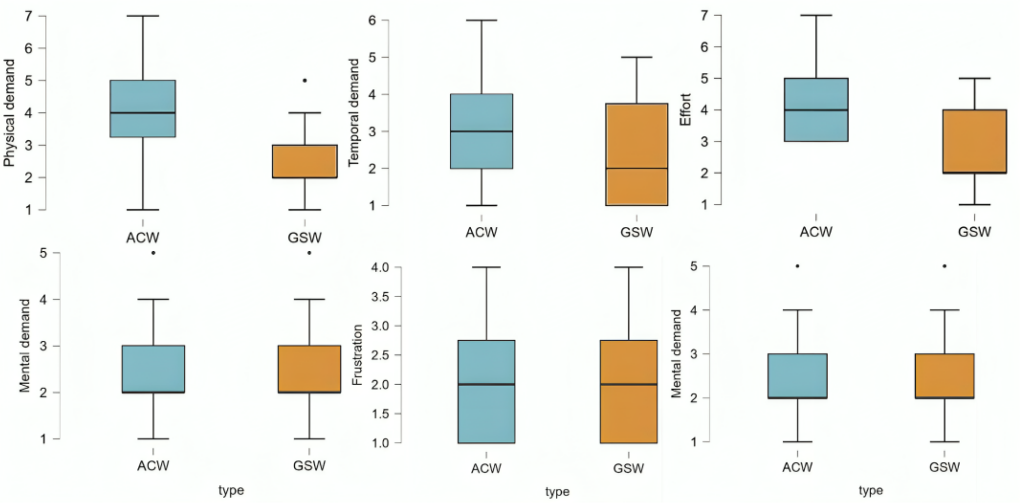

Figure 5.11: Box plots results for NASA-TLX.

one-tail Mann-Whitney U test, which indicates that ACW is significantly slower than GSW (W = 679069.000, p< .001). The box plot results show that the mandibular condition is more precise than the maxillary (see Fig. 13).

5.3.4 NASA-TLX

According to the box plots Figure 5.11, ACW resulted in less mental demand (Likert 2.50/7 vs. 2.67/7, -6%) and frustration (Likert scale 2.00/7 vs. 2.30/7, -13%) compared to GSW. This was an unexpected result, considering that the widget is more complex. We can explain this outcome because this interface is more supportive and intuitive. We also observed that all metrics reject the null hypothesis for normality, and the Mann-Whitney U one-tail test finds that physical demand (W=715.00, p<.001) and effort differ significantly between the two groups (W=709.00, p<.001).

ACW required more physical demand (Likert scale 4.06/7 vs 2.47/7, +64%), temporal demand (Likert scale 2.90/7 vs 2.43/7, +19%), and effort (Likert scale 4.17/7 vs. 2.73/7, +53%) (see Fig. 15). This result was expected and confirmed by the quantitative measurements, which indicated the longer time spent on positioning with unsupported limbs in the air. Participants perceived their performance as slightly superior using ACW (Likert scale 4.7/7 vs 4.6/7, +2%). Users claimed that ACW required more time and was more sensitive to wrist movement, likely meaning it helped achieve better angular positioning. The interviews align with the real performance, and these findings are nontrivial, as in many other VR applications, where user perception differs from objective performance [5].

5.3.5 Preferred Widget

Most participants preferred the ACW (19/30, 63.3%) and rated its aesthetics higher (Likert 5.13/7 vs. 4.83/7, +6%). One user claimed that ACW did not require extra body movement and that the task was easier than GSW, particularly with its thin axes. Many participants reported that ACW was difficult to learn initially, but over time, they adapted and felt faster during the experiment.

5.4 Discussion

The results support the first two hypotheses: ACW provides better 5DOF positional and angular precision and accuracy (H1&H2), an advantage for roll and pitch angles, and along the X and Y components. Angular error is key in implant placement because it can lead to incorrect tool paths during drilling. Furthermore, the widget can assist in complex environments where visibility may be reduced.

The hypothesis claiming ACW is faster (H3) is not supported. This result is partially expected, as the user must pay more attention, exert more dexterity, and spend more time. However, in the specific context of implantology, precision is the most critical aspect, and physical and time demands are secondary. The two hypotheses claiming that ACW reduces mental load (H4) and improves performance compared to GSW (H5) are also supported.

We can conclude that the experiment outcomes, even with similar but not identical modalities and scenarios, align with the advantages of AR interfaces reported in the literature [6], [7]. The questionnaire results showed less mental demand and frustration with ACW, and participants preferred ACW for its performance and aesthetics, validating the design and its principles.

5.5 Chapter Conclusion

We presented a novel collimator widget (ACW), an interactive 5DOF position and angle error augmented reality (AR) visualization tool for dental implantology applications. ACW is based on gestalt reification, the human ability to group geometric elements. The user can quickly and pre-attentively seek the collimation of five (three positional and two rotational) error component widgets (ECWs), taking advantage of three key aspects: component separation and reification, error visual amplification, and dynamic hiding of the collimated components.

Initially, we identified the golden standard widget (GSW) for dental tool positioning in the literature. Then, we presented the design principles and methodology of ACW. We performed a within-subjects (N=30) user test using 32 implant targets, measuring time, error, and usability. ACW performed significantly better, especially in angular (+47%), but also in positional (+19%) precision accuracy, with less frustration (-13%) and mental demand (-6%), but with an expected increase in physical demand (+64%) and task time (+59%). The interview results indicated that ACW was the main preference and was considered aesthetically more pleasant than GSW.

This work has also revealed the importance of angular error, its implications, and how the GSW can be improved, particularly in this aspect. Our widget implementation and the experimental infrastructure built in Unity 3D are designed to be flexible, allowing us to rapidly test different configurations. However, while ACW showed potential, it still had room for improvement, and its evaluation and design did not involve real end-user dentists. Therefore, this widget design has inspired the development of the next MR widget, which is implemented in the following chapter.

In conclusion, we are very encouraged by the positive outcomes of this study and believe that ACW can become the new golden standard, not only for implantology but also for applications in medical and industrial fields (e.g., CAD, welding, assembly, etc.) where 6DOF precision is required.

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Chapter 6

Co-Designed Dynamic Widgets (DW): A Collaborative Approach with Dentists

Chapter Summary

Chapter 5 introduced the Augmented Collimator Widget, which applies Gestalt principles to enhance tool precision in 3D space. However, no dentist has been involved in the design and experimentation of our proposed widget. While the results from Therefore in **Chapter 6** focus on the co-design process with real-world practitioners.

Therefore, this chapter contributes by co-designing MR drill tool manipulation widgets with two expert dentists and three MR experts. The results of co-design are two static widgets (SWs): a simple entry point, a target axis, and two dynamic widgets (DWs), variants of dynamic error visualization with and without a target axis (DWTA and DWEP). We evaluated the co-designed widgets in a virtual reality simulation supported by a realistic setup with a tracked phantom patient, a virtual magnifying loupe, and a dentist's foot pedal. The user study involved 35 dentists with various backgrounds and years of experience. The findings demonstrated significant results; DWs outperform SWs in positional and rotational precision, especially with younger generations and subjects with gaming experiences. The user preference remains for DWs (19) instead of SWs (16). However, findings indicated that the precision positively correlates with the time trade-off. The post-experience questionnaire (NASA-TLX) showed that DWs increase mental and physical demand, effort, and frustration more than SWs. Comparisons between DWEP and DWTA show that the DW's complexity level influences time, physical, and mental demands. The DWs are extensible to diverse medical and industrial scenarios that demand precision.

Contents

6.1 Widgets Co-Design with Dentists

We followed the Co-design methodology proposed by [1], which specifically supports multidisciplinary medical collaboration by a user-centered iterative development process. We construct a co-design group of five experts: two dentists with 15 and 4 years of experience in endodontology and three MR experts with 26, 15, and 5 years of experience. Over four months, we performed one-to-one interviews, live demos, and focus groups [2].

Physical and VR scenarios for the dental room simulations were implemented during the co-design. This approach allowed us to quickly assess altered widget design cycles, as a full AR setup is sensitive to trackers' error and latency. Firstly, the experts discussed the problem of MR widgets in order to evaluate an unbiased clinical dentist's perspective regarding visualization. Afterward, reproduced widgets from the literature were demonstrated. Furthermore, feedback for improvement and user experiment details were iteratively gathered and implemented with adjusted functionalities, particularly widgets' type, behavior, form, size, and material.

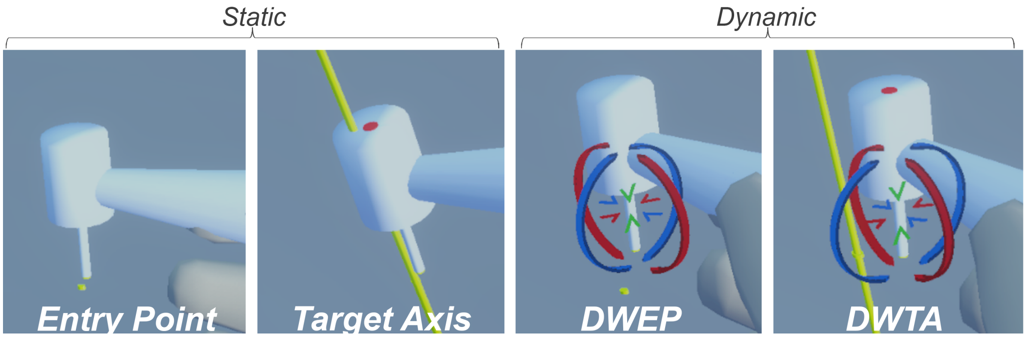

Figure 6.1: Static and Dynamic MR widgets demonstrate only assistive virtual elements; entry point, target axis, DWEP dynamic widget with entry point, DWTA dynamic widget and target axis.

6.1.1 Co-Design Results

At the end of the co-design phase, we answer our RQ_1. As an outcome, we implemented the following MR widgets conditions in a realistic setup (Figure 6.1) with distinctive attributes (static vs dynamic) meeting the diverse needs of dentists when operating, such as visibility, usability, and design preferences.

Two MR widgets are designed as static widgets and two as dynamic conditions Figure 6.1.

We use Unity Platform [3] with a world-fixed dextrorotary coordination system with z (blue) pointing forward to the initial user position, x (red) pointing to the horizontal, and y (green) pointing up on the vertical axis. An unexpected outcome was the discovery that the industry standards of dentistry often support the right hand for the drill tool independently from the user's dominance. Therefore, we designed our widget to be right-handed, considering that most left-handed dentists also use their right hand for dental procedures.

6.1.1.1 Static Widgets (SWs)

Entry Point Widget This widget is the simplest set as it provides the entry point only by a static yellow cylinder of radius r= 1 mm *length*=3 mm. The dentist proposed it due to missing rotational alignment information and feedback. It is a negative control condition that resembles the current "unassisted" method. Since it is known from the literature, it should be included to increase comparability [4]–[6].

Target Axis Widget This widget is most abundant in related works [4], [5], [7]–[9]. It is a yellow cylinder of r= 1 mm, *length*=120 mm with a yellow color for easy identification. The intersection point of the axis with the gingiva provides spatial positioning like the entry point condition, while the axis represents the drill path in space. A centered red disc on top of the drill tool enables alignment with the target axis, similar to the work by Song et al. [10]. Unlike the static Entry Point, it provides pseudo-static feedback of correct spatial positioning and serves as a baseline.

6.1.1.2 Dynamic Widgets (DWs)

Dynamic Widget (DW) [1] provides real-time dynamic feedback of the spatial positional and rotational error, taking inspiration from the study of Dastan et al. [7], which uses the gestalt theory of perception [11]. This approach mimics the behavior of analog measurement tools like mechanical calipers and photographic optical viewfinders. The DW's basic principle is to provide visual feedback using graphical error visualization Figure 6.2. The span error between tool and target is reflected by the mutual distance of forms (Figure 6.2), three positional "**V**"-shaped duos (one per axis component) (Figure 6.2) and two rotational "("-shaped duos (one per 5DOF component) (Figure 6.2). During co-design, we discussed our previous ACW [7] and were inspired to implement our DW. We improved the following features:

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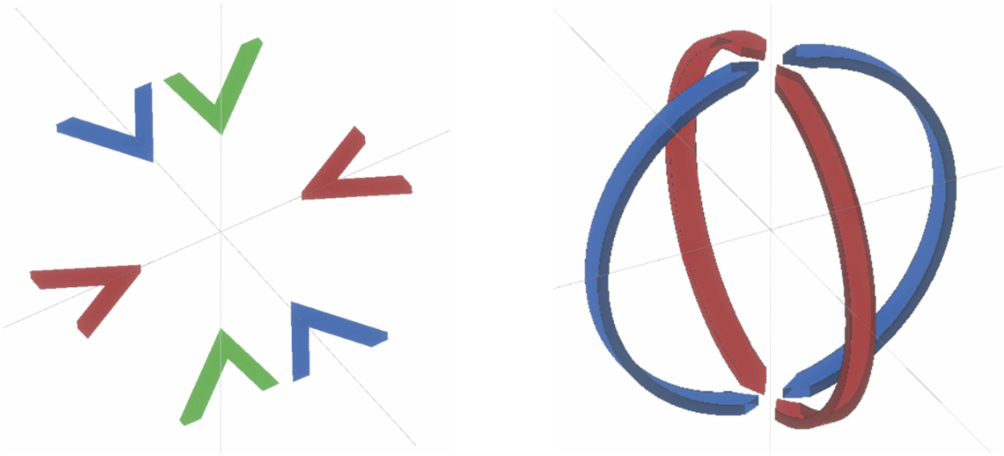
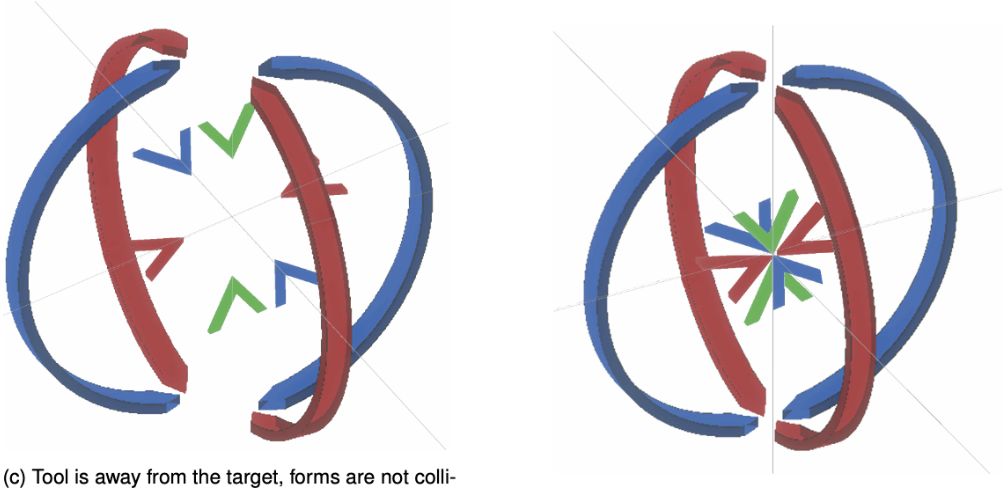
[1] DW open source link: https://github.com/Vr3xMelab/DW.git.



(a) The positional components x, y, and z axis represented as 3D "**V**".

(b) The rotational components, x and y axis represented as 3D "**(**".



(c) Tool is away from the target, forms are not collimated.

(d) Tool is on the target, forms are collimated.

Figure 6.2: Compositions of DW: positional and rotational components (a, b), the tool is far from the target, forms are in the periphery and away from each other (c), the tool is on target, forms are nearby (d)

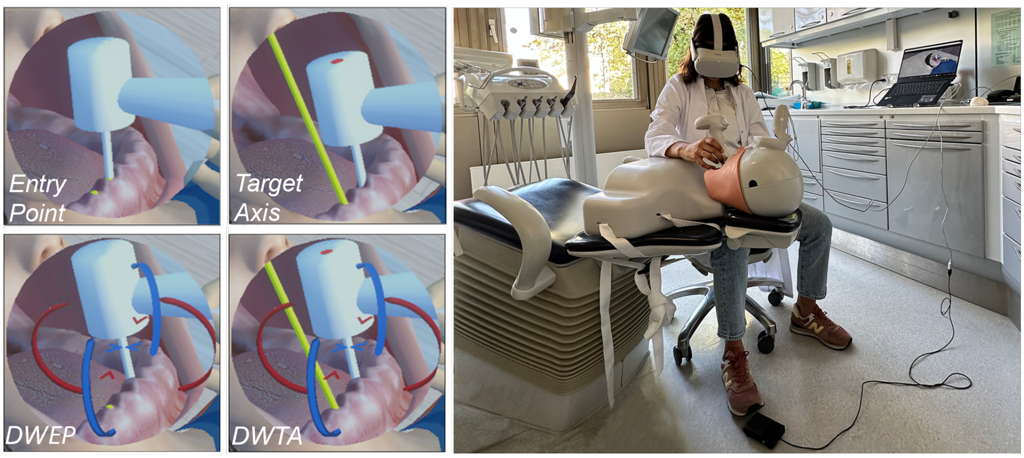


Figure 6.3: Co-designed mixed reality drill positioning widgets: Entry Point, Target Axis, Dynamic widget and entry point (DWEP), Dynamic widget and target axis (DWTA), compared in a realistic setup in the dental room: virtual magnifying loupe (left), tracked phantom and virtual patient, foot pedal, laptop and headset (right).

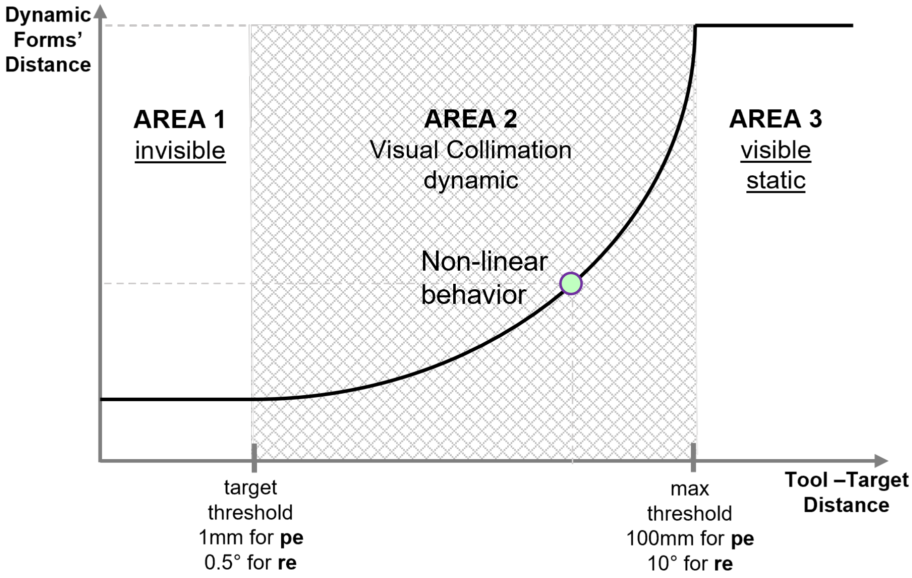


Figure 6.4: Implementation of three dynamic visibility areas: Area 1: Invisible forms, Area 2: Visible Collimation Area with dynamic and non-linear behavior, Area 3: Visible static forms.

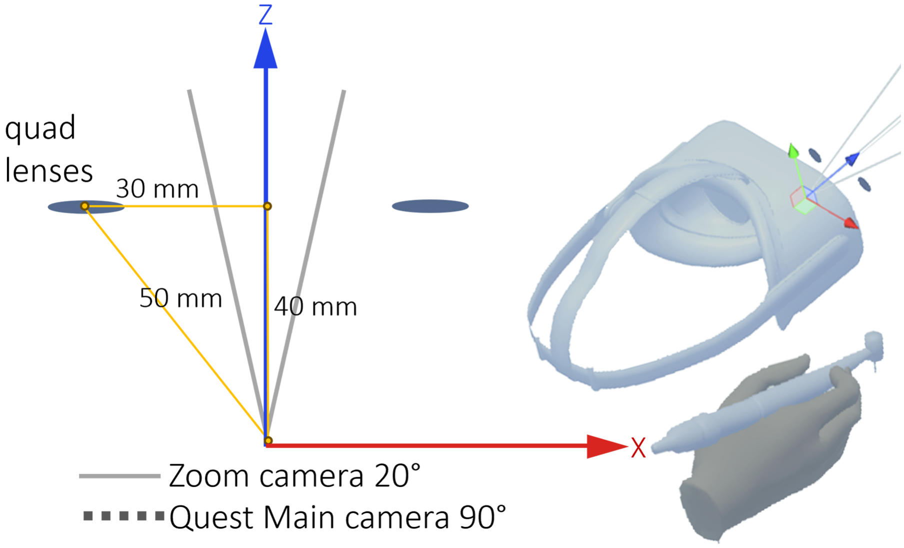


Figure 6.5: Implementation of the virtual magnifying loupe; top view of lenses' angles and positions (left), two quads attached to the headset(right).

- optimization of dynamic visibility areas' threshold parameters;
- applied nonlinear law for the displacement of related form duos;
- implementation of 3D forms instead of 2D textured icons;
- attached the DW closer to the drill tooltip to improve intuitiveness;
- the DW rotation form duos are related to the user's controller rotation instead of locked to the world reference system;
- applied custom shader materials to form duos to prevent visual occlusion by other visual objects in the scene.

Dynamic visibility areas: We defined the positional vectors as tool position (**top**) and target position (**tap**) and the rotations as tool rotation (**tor**) and target rotation (**tar**). We also split the

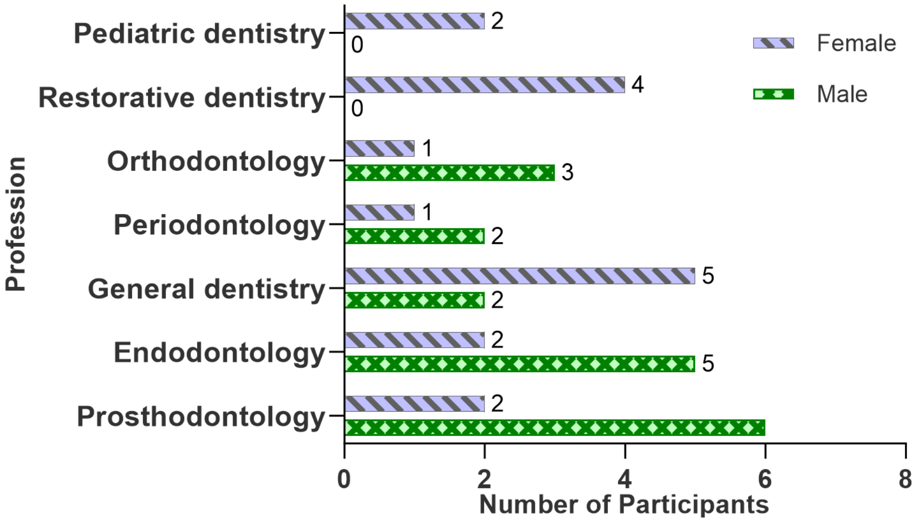


Figure 6.6: Gender/profession of dentists participated in the user study.

spatial positional error into pure positional error (**pe**) and the rotational error (**re**) of the tool and target. We modified the dynamic visibility behavior of our previous work ACW [7]. The main goal of this modification is to reduce visual overload. From our co-design, we assigned the following dynamic visibility areas (Figure 6.4):

- Area 1: Target threshold (tt) = 1 mm for **pe** and 0.5 ° for **re**; these parameters set with dentists' feedback during co-design. The component is hidden when tt has been reached as the user needs no intervention.
- Area 2: Dynamic nonlinear behavior, duos are visualized. This reduces the amplification in the target vicinity and avoids overshooting fatigue (Figure 6.4)

$$\mathbf{pe} = f_{\mathbf{pe}}(\mathbf{tap} - \mathbf{top})^2 \quad \text{and} \quad \mathbf{re} = f_{\mathbf{re}}(\mathbf{tor} \cdot \mathbf{tar}^{-1}) \tag{6.1}$$

- Area 3: Pairs are visualized but static/frozen at a max threshold (mt) = 100 mm for **pe** and 10 ° for **re**, co-designed with the dentists' feedback to avoid being too far away from sight.

Dynamic Widget and Entry Point (DWEP) DWEP combines the DW with the Entry Point widget. This condition provides an almost "DW-only" scenario, where the entry point only indicates the target position.

Dynamic Widget and Target Axis (DWTA) This condition combines DW and static Target Axis widgets. The mixed DWTA gives two references for the dentist to follow during tool manipulation. DWTA evaluates the combined widgets' impact on performance and task load.

6.2 Evaluation

During co-design assessments, it was seen that DWTA might provide better objective and subjective parameters than the other three conditions. Additionally, we noticed that targets were reached faster using the Target Axis and Entry Point widgets; therefore, we hypothesized they would result in less cognitive effort. A within-subject user study was conducted with dentists to analyze our co-design results and compare MR widgets: DWTA, DWEP, Target Axis, and Entry Point conditions. We evaluated the user performance, task load, and preference of MR widgets implemented in co-design sessions. This section includes the details of the user study.

6.2.1 Research Questions and Hypotheses

We set the following research questions for the user test:

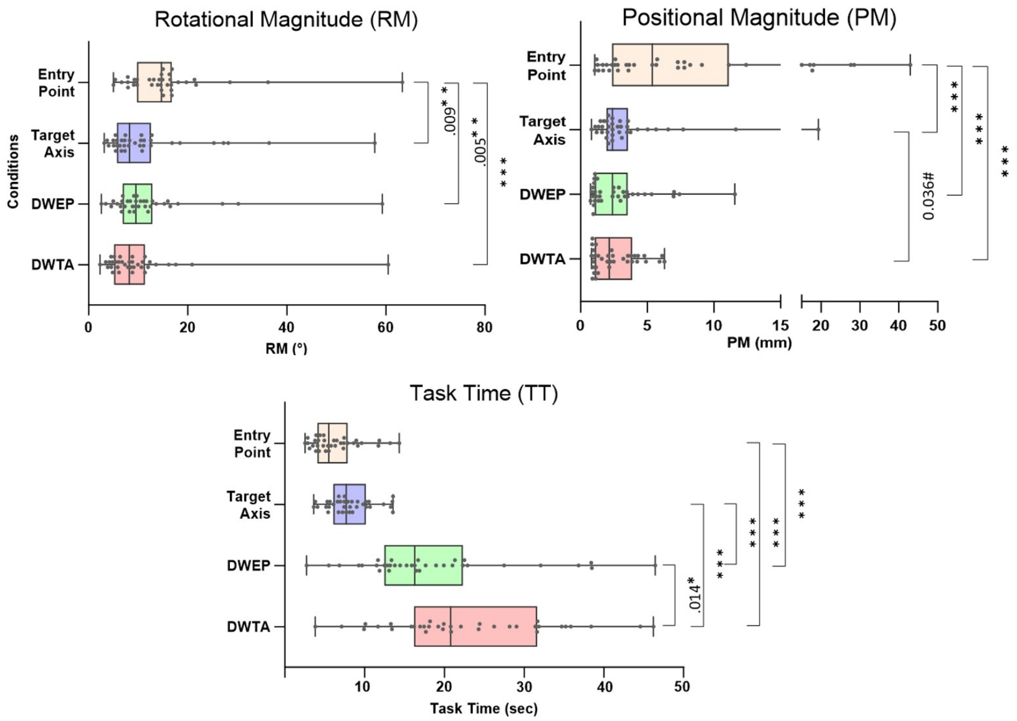


Figure 6.7: Conditions box plot comparisons of user study results (n=35, * = Friedman (pbonf***$\leq$0.001), #= Wilcoxon (p#$\leq$0.05) test): rotational magnitude RM and positional magnitude PM: **Entry Point** is the least accurate, task time TT: Entry Point faster than **DWEP** and **DWTA**, **Target Axis** is faster than DWEP, DWTA and DWEP is faster than DWTA.

- *RQ_1: "What is the co-design outcome regarding widget design, their evaluation criteria and conditions?"*
- *RQ_2: "Which condition is the best-performing and preferred widget in a realistic setup?"*
- *RQ_3: "Are dynamic widgets more precise than static widgets?"*
- *RQ_4: "Does precision impact other variables such as time and task load?"*
- *RQ_5: "Do age and gaming experience influence precision?"*

We stated below the research hypotheses (H_n) following our co-design evaluation:

We set the following hypotheses for RQ_2 and RQ_3:

- **H_1**: DWTA has better precision than other conditions.
- **H_2***a*: DWEP is faster than the DWTA,
- **H_2***b*: DWTA has better precision than DWEP.
- **H_3**: Entry Point "non-assisted method" has the lowest task time.
- **H_4**: Target Axis has less task load than DWs.
- **H_5**: The added complexity of DW increases the task load.

We set the following hypothesis for RQ_4:

- **H_6**: There is a negative correlation between precision and time.

We set the following hypothesis for RQ_5:

- **H_7**: Younger generations and subjects with gaming experience have better precision using DWs.

6.2.2 Participants

Our study was approved by our institutional review board. Informed consent was obtained from each participant. Thirty-five voluntary dentists participated (18 Male, 17 Female) aged 34.34 ± 9.9 years. They belong to various specialties: Eight in prosthodontology, seven in endodontology,

Figure 6.8: Experiment setup; Phantom model tracked with the left controller (left). The right hand is for tool handling (top-right), and the foot pedal is the input device (bottom-right).

seven in general dentistry, three in periodontology, four in orthodontology, four in restorative dentistry, and two in pediatric dentistry Figure 6.6. This group doesn't include the first two dentists participating in the co-design phase. We collected participants' ages, years of experience in dentistry, AR/VR experience, and gaming rates.

6.2.3 Co-designed Setup

We used an AR simulated in VR setup as supported by its validity in literature [12]–[14]. As a result of co-design, we built a realistic setup, supported in a physical dental studio, to imitate the body pose and movements. The hardware comprised an Oculus Quest 2 (Meta, CA, USA) HMD, which was connected to a laptop PC with a USB-A cable, a Foot Switch USB-A foot pedal (Xiatiaosann, Guangzhou, China), and two Meta Quest 2 controllers (Meta Platforms). The right-hand controller was represented in VR by a virtual hand grasping a drill tool (Figure 6.8). To achieve realistic drill handling, users turned the right-hand controller and held it backward. A handmade drill tooltip was attached to the right-hand controller to mimic the drill tool. The left controller tracked the virtual patient's head position on the real phantom to provide arm/hand rest reference to the participants (Figure 6.8).

Dental Room and Phantom We used a dental room with a physical phantom as described in literature [4]–[6], [8]. The dental unit's backrest angulation was adjusted to a horizontal position, and the physical phantom was affixed to the dental unit with belts (Figure 6.3). The dental stool was positioned on the right side of the phantom and parallel to the dental unit. The dentists were asked to sit on the stool to simulate the operative stance. In VR, we designed a dental room arrangement with a static avatar patient and dental unit. All targets are positioned only on the virtual patient's mandible.

Foot pedal We simulated the dentist's drill control using Unity 3D input action linked to the USB-based pedal (Figure 6.8). Participants confirmed the tool manipulation on each target by pressing the pedal. After each pedal hit, sound feedback was provided; afterward, the next target appeared in the mandible.

Virtual Loupe Dentists suggested a VR magnifying loupe during the co-design process, which is also supported by literature with positive outcomes in surgical tasks [15]–[19]. In each condition, the virtual loupe was attached to the headset camera for a focused task field of view to ensure better posture and minimize physical strain. The VR loupe was implemented using two circle quads (r= 10 mm), a zoom camera, and render-texture material in Unity. Each quad has a 30 mm distance from its center point. Quads were attached to the main camera with a 50 cm offset and followed the head movement (Figure 6.5). Using post-processing in the main camera, we added a blur effect to enhance the scene's depth perception.

6.2.4 Procedure and Drill Positioning Task

We introduced the experiment research problem and the four widgets, with a neutral and unbiased description of their function, followed by the test procedure instructions (Figure 6.9). Participants sat on the dental stool and wore the Oculus Quest 2 headset. The experiment commenced with a training scenario in which each condition was presented sequentially. Afterward, the main experiment started. A balanced Latin square was used to establish the order of the MRDPW conditions (Figure 6.3).

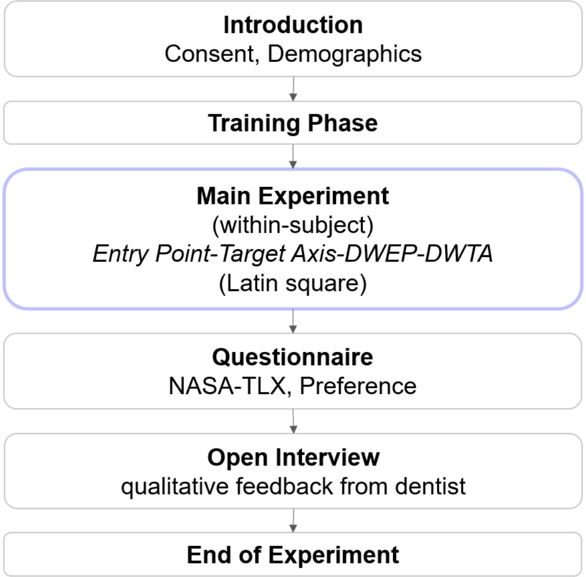


Figure 6.9: User Study protocol overview.

The user task involved positioning and orienting the drill to the indicated target as precisely as possible. An active depth drilling task was not included. The foot pedal was pressed once the dentist was satisfied with the precise drill tool manipulation. The pedal hit saved the error value entry and proceeded with the next target. Targets appeared singly in random order. Each condition involved 16 repetitive tool manipulation tasks for each subject. After completing all positioning tasks for one condition, the next scene was launched. Objective metrics were automatically saved. Following the main experiment, participants were tasked with completing a subjective questionnaire. Subsequently, we sought dentists' opinions on the specific condition/setup/widget through an open interview session. The entire user study took approximately 40-45 minutes.

6.2.5 Metrics

We collected the following parameters during our user study:

Positional Error: The positional magnitude (PM) was calculated to assess the precision of distance error between the drill tool-tip and the entry point target. Separated metrics for the distance along the x, y, and z-axis (PX, PY, PZ) were measured in millimeters.

Rotational Error: The rotational magnitude (RM) was calculated to assess the precision of rotational error between the drill tooltip and entry point axes. Separate metrics for the delta angle along the x and z-axis (RX, RZ) were measured in degrees.

Task Time: The elapsed time between the single target display and foot pedal press, measured in seconds.

Task load: After the experiment, participants compiled a NASA-TLX [20] questionnaire (Likert 7 scale), including mental demand, physical demand, temporal demand, effort, and frustration.

User Preference and Opinions: Following the questionnaire, we conducted post-experiment open interviews with the participants to record their preferences and gather their opinions.

6.2.6 Statistics

Data was analyzed using JASP software (version 0.18.3.0, University of Amsterdam). Normality was assessed using the Shapiro-Wilk test, which revealed a non-Gaussian data distribution. First, descriptive data analysis was performed for RM, PM, and TT. Consequently, we employed the non-parametric Friedman test to assess statistical significance for paired samples alongside Kendall's W to measure the effect size. Bonferroni corrections were used for post hoc comparisons (pbonf$\leq$.05). We further conducted a Wilcoxon test to compare two independent samples that had a mean difference (md), whether their mean ranks statistically differ (p$\leq$.05). Only significant comparisons from the Wilcoxon test are reported in the results section. Additionally, we calculated Pearson's correlation coefficient (r) to measure the linear relationship between precision and time variables. Significance was assumed at r-value$\leq$0.6:strong,$\leq$0.4:moderate,$\leq$0.2:weak,<0.2:very weak.

6.3 Results

6.3.1 Objective Measures

All participants performed all tasks of precision-focused drill tool manipulation on sequential targets for MRDPW conditions. In total, we collected 2240 samples (16 tasks x 4 conditions x 35 participants) for objective measures. The results are summarized below in a concise manner:

Rotational Error: RM, RX, RZ RM: The descriptive statistics are DWTA (9.96 ° ± 9.72), DWEP (12.09 ° ± 10.02), Target Axis (12.29 ° ± 11.01), Entry Point (15.94 ° ± 10.32). The Friedman test revealed statistical significance for RM (x^2= 35.81, p<.001, Kendall's W= 0.34). Post hoc Dunn-Bonferroni corrections highlighted that Enry Point has the least RM precision (Figure 6.7).

RX: The Friedman test demonstrated significance in RX (x^2= 62.72, p<.001, Kendall's W= 0.59). Post hoc Dunn-Bonferroni corrections indicated that Entry Point is the least precise condition, and Target Axis is less precise than DWTA (Figure 6.10). Further, a Wilcoxon test revealed significance in DWEP<Target Axis (md =1.22, z=-2.22, p=.026*).

RZ: The Friedman test indicated significance for RZ (x^2= 70.26, p<.001, Kendall's W= 0.66). Post hoc Dunn-Bonferroni corrections demonstrated that Entry Point is the least precise condition and Target Axis is less precise than DWEP and DWTA (Figure 6.10).

Positional Error: PM, PX, PY, PZ PM: The descriptive statistics are DWTA (2.58 mm ± 1.69), DWEP (2.85 mm ± 2.41), Target Axis (3.55 mm ± 0.81) and Entry Point (8.43 mm ± 1.06). The Friedman test yielded significant results for PM (x^2= 19.90, p<.001, Kendall's W= 0.19). Subsequent post hoc Dunn-Bonferroni corrections were applied. The results demonstrated that Entry Point is a less precise condition (Figure 6.7). While non-significant median values were observed, a Wilcoxon test revealed significance for DWTA < Target Axis comparisons (md= 0.96, z=2.09, and p=.036).

PX The Friedman test demonstrated statistical significance in PX (x^2 = 15.65, p=.001, Kendall's W= 0.15). Post hoc Dunn-Bonferroni corrections revealed that Entry Point is the least precise condition (Figure 6.10).

PY The Friedman test indicated statistical significance for PY (x^2= 24.46, p<.001, Kendall's W= 0.23). Post hoc Dunn-Bonferroni corrections revealed that Entry Point is the least precise

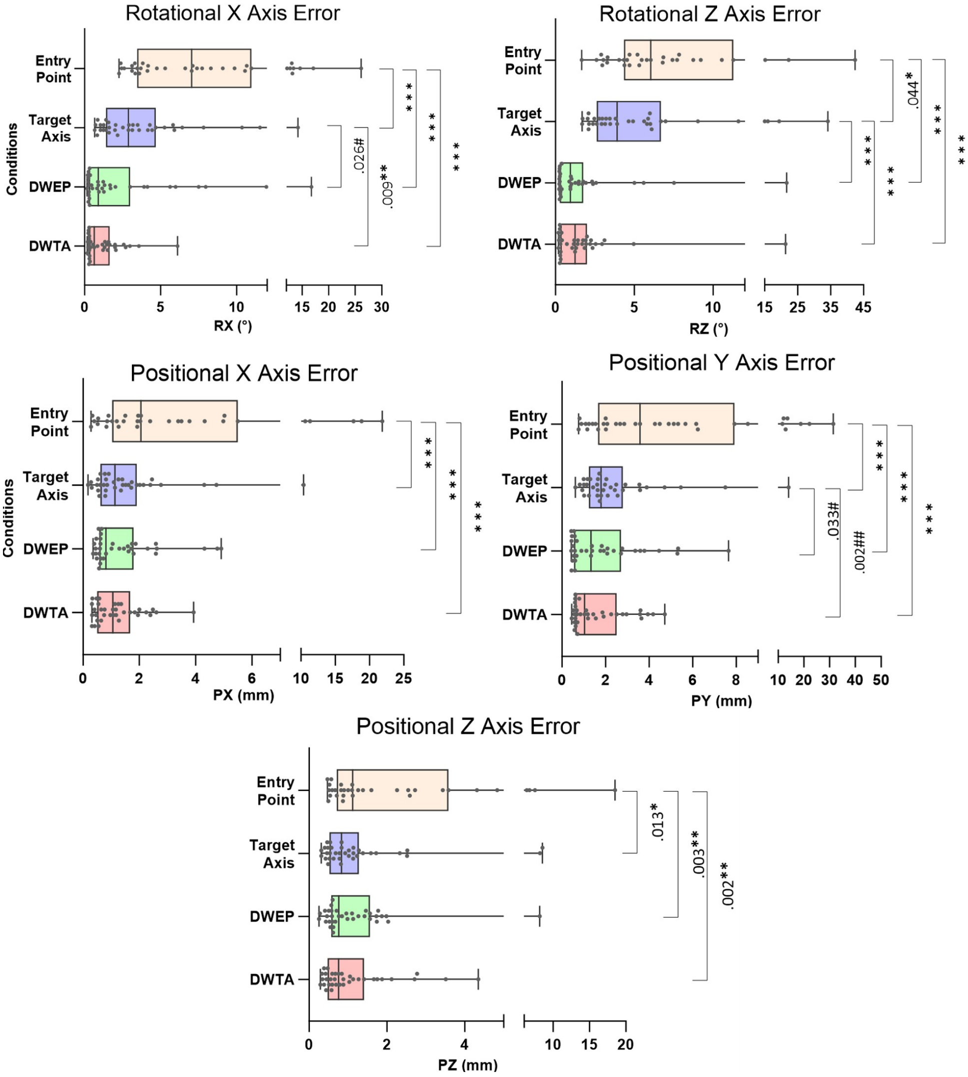


Figure 6.10: Conditions Box plot comparisons of user study results (n=35, * = Friedman (pbonf***≤0.001), #= Wilcoxon (p#≤0.05) test) for Rotational X and Z Axis errors (RZ and RX) and Positional X, Y, and Z errors (PX, PY, PZ): **Entry Point** is the least precise in RX, RZ, PX, PY, PZ. **Target Axis** is less precise than **DWTA** in RX, RZ. Target Axis is less precise than **DWEP** in RZ.

condition (Figure 6.10). Further, the Wilcoxon paired samples t-test showed DWEP<Target Axis (md= 0.86, z=2.12, p=.033*) and DWTA<Target Axis (md=0.25, z=2.99, p=.002**).

PZ: The Friedman test yielded statistical significance in PZ (x^2= 12.90, p=.005, Kendall's W= 0.12). Post hoc Dunn-Bonferroni corrections demonstrated that Entry Point is the least precise condition (Figure 6.10).

Task Time The descriptive statistics for TT; Entry Point (6.39 sec ± 3.02), Target Axis (8.17 sec ± 2.78), DWEP (18.46 sec ± 9.88), DWTA (23.03 sec ± 10.32). The Friedman test revealed statistical significance (x^2= 75.61, p<.001, Kendall's W =0.72). Post hoc Dunn-Bonferroni corrections applied results yielded significance for Entry Point < DWEP, DWTA (pbonf <.001***), Target Axis< DWEP, DWTA (pbonf<.001***) and DWEP < DWTA (pbonf=.014*) (Figure 6.7).

6.3.2 Subjective Measures

Observations During the experiment, the observer noted the following events. Five participants exhibited excessive body movement in Entry Point and Target Axis conditions. One user asked

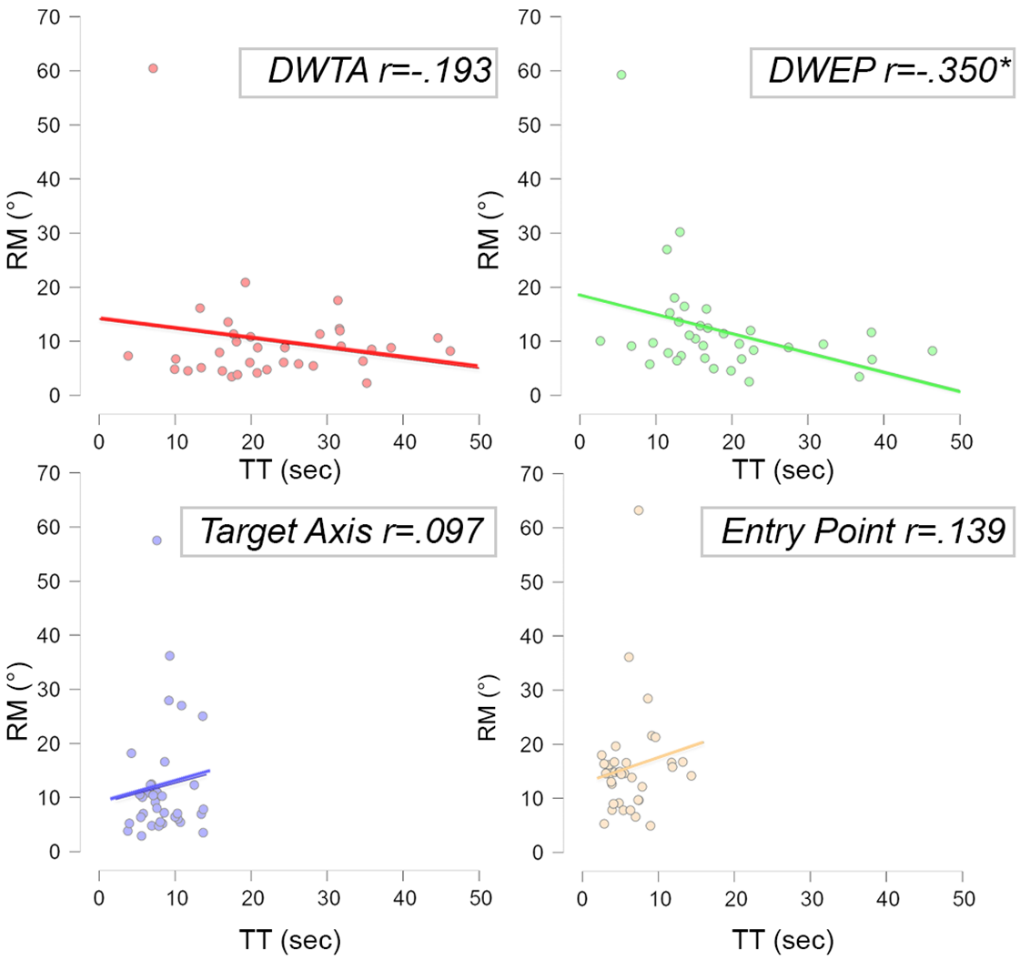


Figure 6.11: RM-TT Correlations: DWEP has a significant negative correlation; RM precision requires time. Correlation strengths (r) are presented (r-value≤0.6:strong,≤0.4:moderate,≤0.2:weak,<0.2:very weak).

for a larger virtual loupe. One experienced blurry vision, and another reported eye strain. A 61-year-old dentist experienced neck problems and took longer to complete the task.

NASA-TLX Participants compiled the questionnaire about the task load (Figure 6.16), age, background, year of experience, gaming skill rate, and preference. On average, they had nine years of experience in dentistry $5\,\bar{X}$ (min 1, max 36 ± 9 IQR). They rated their gaming skills as 3.31 ± 2.01 / 7 and their knowledge of AR/VR applications as 2.7 ± 1.75 / 7 (having tried AR/VR apps at least once). All were right-handed, except two left-handed and one ambidextrous. Nevertheless, all could use the right hand and the right foot for the task.

Mental Demand: Entry Point and Target Axis had lower mental demand than DWEP and DWTA (p<.001***). DWEP<DWTA (p=.047*) (Figure 6.16).

Physical Demand: Entry Point and Target Axis had lower physical demand than DWEP and DWTA (p<.001***). DWEP<DWTA (p=.016*)(Figure 6.16).

Effort: Entry Point and Target Axis required less effort than DWEP and DWTA (p<.001***) (Figure 6.16).

Frustration: Entry Point had less frustration than DWTA, and Target Axis had less frustration than DWEP or DWTA (p<.001***) (Figure 6.16).

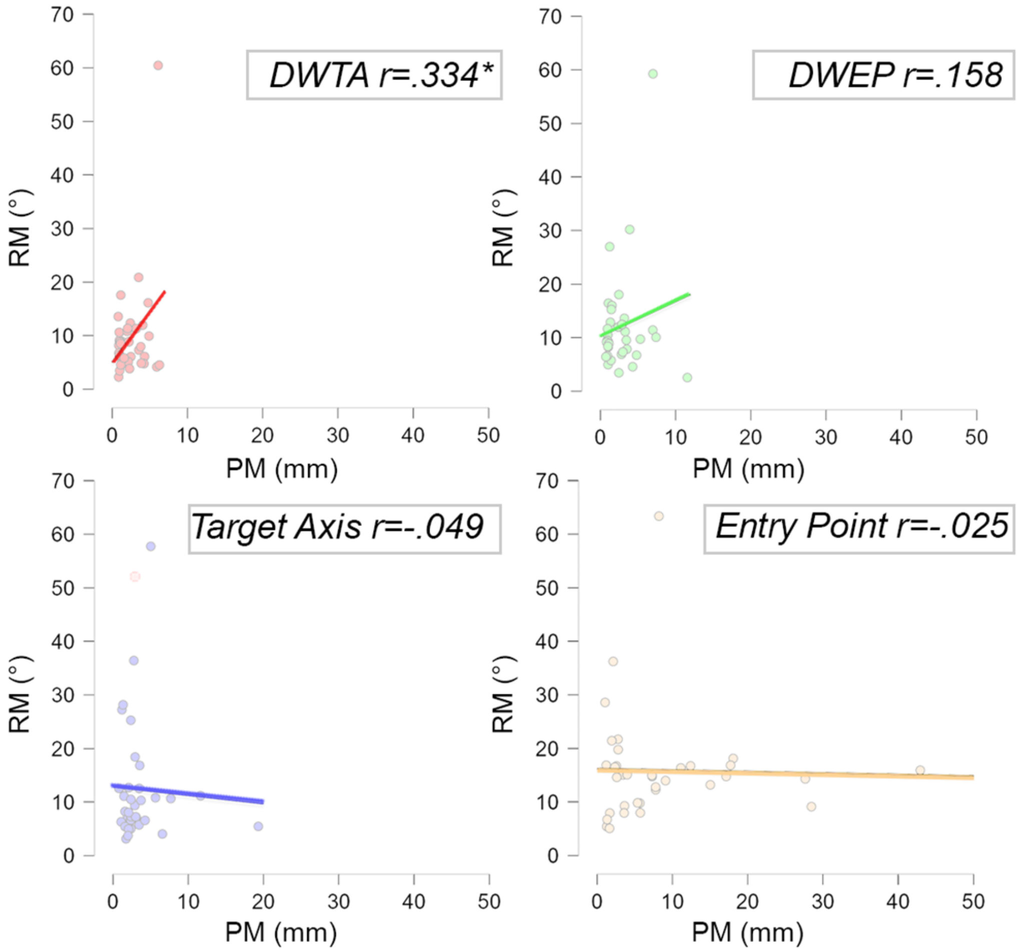


Figure 6.12: RM-PM Correlations: DWTA has a significant positive correlation pointing to better RM precision leading to better PM precision.

6.4 Discussion

6.4.1 Objective Measures Analyses

In addressing our research questions, we observed significant improvement of DWs over static Target Axis in positional and rotational precision. Both DWs outperform Target Axis in positional PX and rotational RX and RZ. Furthermore, DWTA is more effective in PM than Target Axis, which supports our $\mathbf{H}_1$.

On the other hand, DWs have a time trade-off comparing SWs. This outcome aligns with existing literature [7] in which DWs are significantly more precise but slower than SWs. This is an expected and interesting finding as it highlights the value of DWs in providing better precision and the trade-off in execution time. Interestingly, $\mathbf{H}_2 a$ is supported, and DWEP is faster than DWTA, indicating that more complex widget design influences task time. However, unlike our expectations, $\mathbf{H}_2 b$ is not supported, and the two dynamic widgets did not differ statistically in positional and rotational precision.

Besides, our $\mathbf{H}_3$ is supported; the Entry Point is faster than the other conditions. However, although the widget shows the exact entry point, the Entry Point is the least precise condition in PM and for each axis component (PX, PY, and PZ). Target Axis provides better positional precision than Entry Point, indicating that Entry Point requires additional information to indicate the target position. Entry Point is also the least precise in rotational precision (RM, RX, and RZ), which is evident since the widget doesn't include rotational hints.

During the co-design phase, dentists stressed the importance of keeping positional and

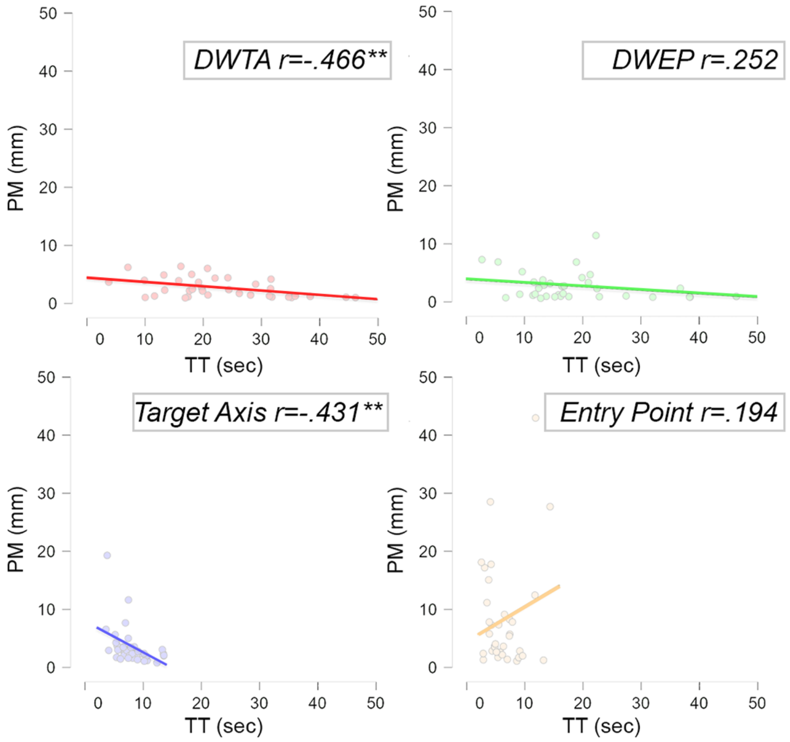


Figure 6.13: Correlations of PM-TT: DWTA and Target Axis demonstrate negative correlation, revealing that more time trade-off ensures better PM precision.

rotational error low as key factors compared to task time. We see that the quantitative results are similar and in line with the literature regarding the advantages of MR in assisted tool manipulation, [5], [7], [21]. Additionally, we executed correlations between time-positional and rotational precisions to investigate MR widgets' performances further. The DWTA (r=-.466**) and Target Axis (r=-.431**) are related by the significant negative correlation between PM and TT (**H**$_6$), proving the effect of spending more time results in better positional precision (Figure 6.13).

DWTA (r=.334*) shows a significant positive correlation between RM and PM, demonstrating that attention to the widget can bring better precision in position and rotation (Figure 6.12).

DWEP (r=-.350*) demonstrates a significant negative correlation between RM and TT, which supports our **H**$_6$, proving that more time is acceptable to reach rotational precision (Figure 6.11). These results highlight that the 3D dynamic widgets provide better PM and RM precision at the price of a time trade-off.

Our **H**$_7$ is also supported; when comparing age and precision for DWTA, junior participants performed with less PM (r=.464**) and RM (r=.337*) precision. This result can be explained by the minor familiarity of senior dentists with utilizing complex widgets. In support of this, subjects with gaming experience perform better for the DWTA (r=.368*) (Figure 6.14), also indicating their ability to understand the most complex widget of the set.

6.4.2 Subjective Measures Analyses

NASA-TLX As expected, Entry Point and Target Axis, being the simplest to understand and the fastest to execute, resulted in lower Mental, Physical, and Effort demand scores than dynamic DWTA and DWEP, which partially supports **H**$_4$. The frustration rate was lower for Target Axis than DWTA-DWEP, while Entry Point was DWTA only. These results indicate that Target Axis is relevant in literature [7] as an immediate and simple to understand widget. Also, our **H**$_5$ is partially supported, and simpler DWEP has less mental and physical demand than DWTA. These results differ from the previous study by [7], in which our DWs yielded more mental demand and frustration than SWs.

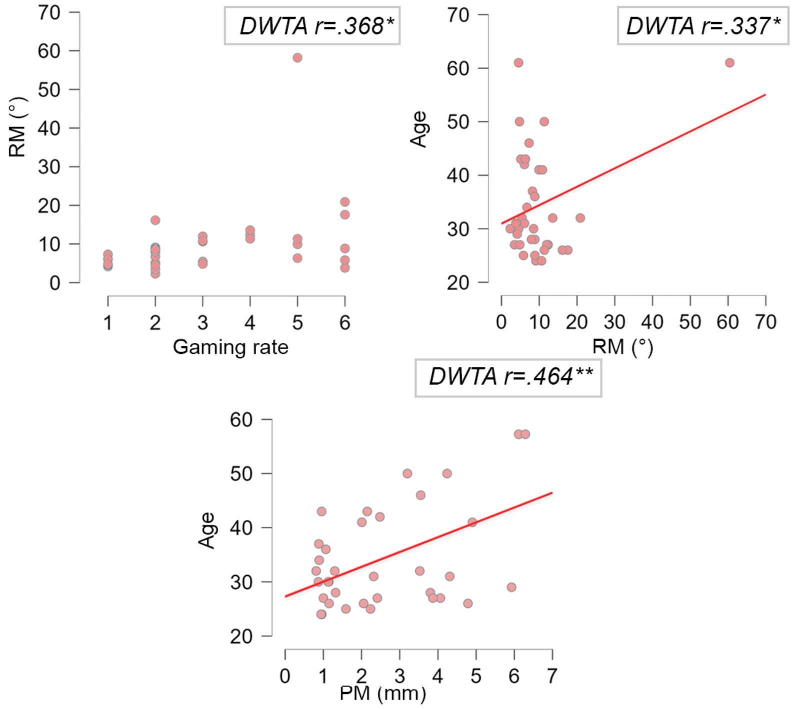


Figure 6.14: Positive DWTA correlations: Subjects with better gaming experience, younger generations have more precision.

Preference Target Axis singularly is the preferred with 16/35 dentists. It is curious to notice that this preference comes from junior and senior dentists (Age of experience 3 $\bar{X}$, min 1-max 36, 13.25 IQR). Despite this preference, observers noted that the Target Axis and Entry Point required more body movement and position changes during the task. Furthermore, participants mentioned that P_{10}:"*Target Axis is straightforward however it is challenging to align rotations precisely*" and P_{18}:"*Target Axis was perceived as irritating and made orientation difficult.*"

DWTA was preferred from 12/35 dentists of all seniority levels (Age of experience 6.25 $\bar{X}$, min 1-max 34, 5.75 IQR). This choice supports the idea that having direct references to the point and axis of Target Axis is a key graphical cue for this widget. Besides, 7/35 participants (Age of experience 4 $\bar{X}$, min 1-max 17, 12 IQR) preferred DWEP. Participants stated about DWs; P_7: "*With training the DW could potentially improve usability*," and P_{14}: "*DW could enhance precision; training with the DW is the optimal choice.*" One user praised the DW's spatial support: P_{16}:"*The frontal axis was challenging to comprehend; the DW is a valid solution.*". Another participant without prior experience with AR/VR declared that P_{17}:"*DW is challenging, Target Axis is demanding to perceive orientation.*"

Interestingly, Entry Point has no preferences. It is remarkable how real usage showcased the limitations. P_7: "*I felt insecure about the precision*" and P_{25}:"*Entry Point is perceived as uncertain and more demanding for precision.*" This indicates that dentists want additional navigation during the tool manipulation and teaches us how MR interface design must confront previous procedures to be accepted by end users.

Overview Although the Target Axis is the most preferred, DWs aggregated preference (12+7) is superior to SWs (19 vs. 16). This result may indicate the potential of DWs, but the current limits of proposed implementations in managing effort vs performance tradeoff. To enhance the comparisons of MR widgets across multiple parameters, we employed radar plot graphs as illustrated in Figure 6.15. Each condition has been assigned a rating (+1 point) based on the results, significantly outperforming the other conditions. This graph presents a nuanced perspective on

Figure 6.15: Radar-plot graphics for MRDPW conditions overview; Entry Point, Target Axis, DWEP, DWTA, and user preference written in the center of each plot(*up*).

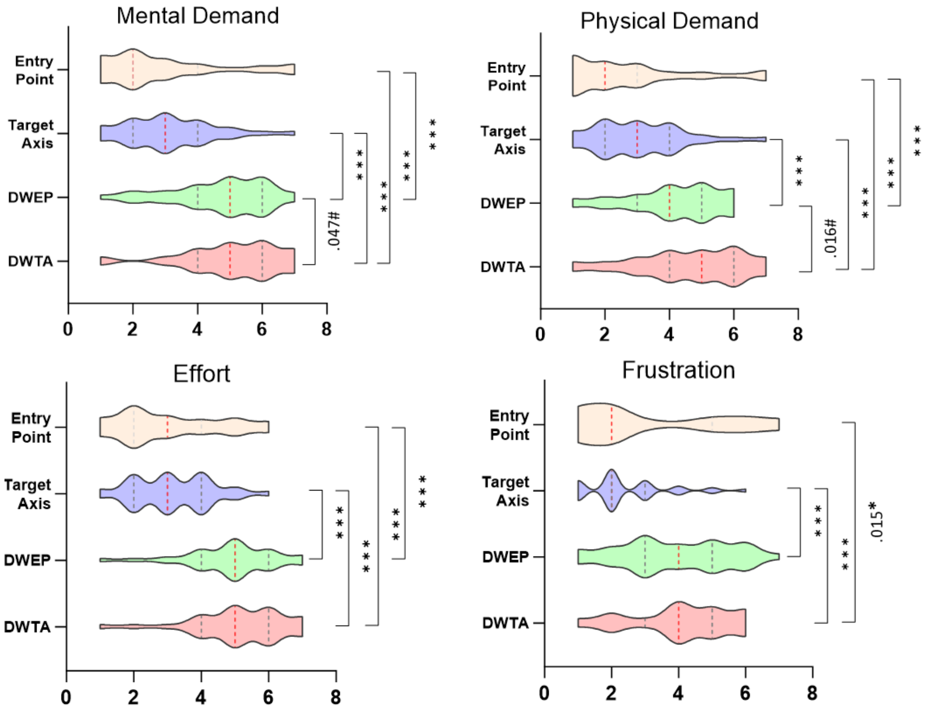


Figure 6.16: NASA-TLX results, (n=35, * = Friedman (pbonf***≤0.001), #= Wilcoxon (p#≤0.05) test), Entry Point and Target Axis have lower task load than DWEP and DWTA.

the strengths and weaknesses of each widget compared to others.

6.4.3 Limitations and Future Work

In this study, we focused on the co-design of MR widgets. The efficacy of our designs was evaluated solely by the tool manipulation task. Several other tasks relevant to the surgical workflow, such as active drilling or precision maintenance, have not yet been included and could influence the subjective and objective performance of the MR widgets. Moreover, in our setup, the mandibular model was absent in the phantom mouth, resulting in less haptic feedback than in a realistic setting. Additionally, the realistic patient movement could not be included since the study was conducted in *in vitro*. The AR simulation in VR was implemented for two primary reasons: Firstly, our study focuses on the visual and dynamic feedback that can be effectively simulated and evaluated within a VR environment. Secondly, the technological limitations of current AR devices (tracking, precision, and latency) may influence the repeatability of the results. However, widgets' performance may be confirmed in real AR setups in future studies. Another limitation is the increased frustration of the presented dynamic widgets. We want to address it in future works with a direct design indicating the path to follow. And exploring different DW referential position configurations (attached to the target or displayed as a screen fixed).

6.4.4 Takeaways

The DW capability to improve dentist's performances in realistic settings is a key result of this work but also sheds light on the interface trade-off between precision (position and rotation) and task load and its impact on user preferences. Furthermore, analyses reveal interesting correlations between user demographics (such as age and gaming experience) and familiarity with the proposed complex and dynamic interfaces. This aspect opens to the crucial role of training for dynamic and innovative widgets design DWs. Finally, we provide the DW scripts and all graphical assets with an open-source license to foster future research in replication, evaluation, and improvement of next-gen interfaces.

6.5 Chapter Conclusions

We carried out the MR dynamic widgets' co-design process for drill positioning involving two expert dentists and three MR experts. We compared two dynamic variants to two static MR widgets. The multidisciplinary process resulted in benefits for dynamic widgets' positional and rotational precision and a trade-off regarding mental and physical effort and frustration. We can conclude that the dynamic widget (DW) design is better than the Static Widgets (SW), as the variants with the highest performance and preference among participants were the dynamic widgets. These DWs outperformed the Sws regarding precision and user preference, making them the preferred choice in the study. A more direct affordance supported by cognitive perception theory must be investigated further. The value of this research demonstrates that DW's designs are documented modular and easy to reuse. In future scenarios, DWs can be easily applied to other medical or industrial scenarios [22]–[26], including manufacturing and assembly maintenance, with clear benefits in terms of safety, efficiency, and better quality of life for the workers.

In conclusion, this chapter by;

- Co-design of MR widgets with three MR experts and two dentists.
- As a result of co-design, the following widgets are implemented. Two static: ***Entry Point***, and ***Target Axis*** inspired by literature. Two novel non-linear behaviors Dynamic Widgets: ***Dynamic widget with Entry Point*** and ***Dynamic widget with Target Axis***.
- Evaluation of MR widgets with dentist subjects of various experience levels in a co-designed realistic setup.

Supplemental Material

DW's open source link is provided as supplemental materials AT https://github.com/Vr3xMelab/DW.git.

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Part 5: Thesis Conclusion

Chapter 7

Discussion

This thesis presented the development and evaluation of various mixed-reality (MR) widgets designed to improve the precision and usability of dental tool manipulation. The MR widgets explored in this research include the **Virtual Stigmometer Widget (ViSti)**, **Augmented Collimator Widget (ACW)**, and the **Dynamic Widgets (DW)**, which were co-designed with dentists. These widgets aimed to facilitate precise tool alignment during dental implant procedures while reducing cognitive load and improving task performance.

Comparing Widget Performance: ViSti, ACW, and DWs

Precision and Task Load Trade-Off: Evaluating the ViSti, ACW, and DW widgets highlights several important insights regarding precision and task load. The **Virtual Stigmometer Widget (ViSti)** in Chapter 4 uses a focus-based mechanism to reduce cognitive load by providing real-time feedback about tool manipulation. The results from user studies showed that the ViSti significantly reduced frustration (-43%) and mental demand (-19%) compared to the traditional golden standard widget (GSW). However, it also led to higher physical demand (+33%) and increased effort (+34%), which suggests that while cognitive load is alleviated, the physical and temporal demands may be higher.

The **Augmented Collimator Widget (ACW)**, discussed in Chapter 5, incorporated the Gestalt principles of error amplification and dynamic feedback to improve both positional (+19%) and angular (+47%) precision. However, this improvement came with increased physical demand (+64%) and task time (+59%). The ACW's design, which dynamically amplifies error components, effectively improved precision but increased the time and effort required for tool manipulation. This shows the inherent trade-off between precision and efficiency in MR widget design.

Finally, the **Dynamic Widgets (DW)**, co-designed with dentists as presented in Chapter 6, also demonstrated superior precision in both positional and rotational accuracy. In precision, these widgets outperformed static widgets, such as the Entry Point and Target Axis. However, dynamic widgets also required significantly more time to complete the tasks compared to simpler static widgets. This reinforces the trade-off observed in the other widgets between precision and task completion time.

Limitations from Each Widget Design

Each chapter in this thesis presents valuable contributions to developing MR widgets for dental procedures. However, there are limitations associated with each study:

Chapter 4 – Virtual Stigmometer Widget (ViSti)

- **Limited Scope of Evaluation:** The evaluation of the ViSti was limited to task load evaluation with no-expert user study (30 participants), which may not fully represent the dentists.
- **Physical and Temporal Demands:** The ViSti, while reducing cognitive load, led to increased physical and temporal demands. This highlights the need for further ergonomic optimization.

Chapter 5 – Augmented Collimator Widget (ACW)

- **Increased Time and Effort:** While the ACW improved precision significantly, it also led to a higher time trade-off, which could be destructive in real-world clinical situations where time is crucial.
- **Limited Setup Evaluation:** The use of VR for testing the ACW limits the ability to evaluate the true performance of the widget in a real AR setup, where tracking issues and device limitations may affect accuracy.

Chapter 6 – Co-Design of Dynamic Widgets (DW)

- **Complexity of Design:** The complexity of the dynamic widgets, particularly DWTA, resulted in higher mental and physical user demands, which could limit adoption in clinical practice.

User Preferences and Practical Implications

User Preferences and Experience: The results indicate a clear distinction between static and dynamic widget preferences. The **ViSti** and **ACW** were praised for reducing cognitive load, but users noted that these designs increased physical demand. The **Dynamic Widgets (DW)**, particularly **DWTA**, received favorable feedback, even though they increased physical and mental load. The preference for DWs, especially from younger users with gaming experience, suggests that dynamic feedback can be effective when properly designed.

Practical Implications: While static widgets like the Entry Point and Target Axis were faster and easier to use, they did not provide the necessary precision for complex dental procedures. This highlights the critical need for dynamic, real-time feedback in precision tasks. However, dynamic widgets' increased physical and mental demands should be considered when designing for clinical environments, where user comfort and efficiency are paramount.

The Role of Gestalt Principles in Widget Design

Gestalt principles—proximity, similarity, continuity, and closure—were central to the design of the ViSti, ACW, and DWs. These principles helped structure the visual feedback in a way that aligns with the brain's natural processing capabilities. For example, the **ViSti** used the collimation principle, where the visual cues became clearer as the tool aligned with the target. Similarly, the **ACW** and **DWs** employed principles of proximity and continuity to direct the user's attention and guide the tool manipulation. Despite their effectiveness in improving usability, these principles also introduced challenges related to visual clutter and cognitive overload, particularly in dynamic interfaces.

Key Takeaways

The key takeaways from this thesis research are as follows:

- **Precision-Task Load Trade-Off:** All MR widgets developed in this research improved precision but at the cost of increased physical demand, mental load, and task time.
- **User Preferences:** Dynamic widgets, particularly DWTA, were preferred by users for their precision, but simpler static widgets (e.g., Entry Point) were favored for their speed and ease of use.
- **Gestalt Principles:** The application of Gestalt principles significantly improved widget design by leveraging the human perception's natural ability to group and process visual information. However, there remains a balance to be struck between precision and cognitive load in dynamic interfaces.
- **Real-World Applicability:** The dynamic widgets have significant potential in improving the precision of dental tool manipulation but must be further refined to reduce the trade-offs in time and physical demand for use in clinical settings.

The insights gained from this work offer a foundation for future improvements in both dental practice and other fields requiring precise tool alignment and manipulation. Moving forward, further refinement of these technologies, emphasizing reducing physical and mental load, will be critical for maximizing their potential impact in clinical environments. The broader applicability of these MR widgets extends beyond dentistry, paving the way for enhanced precision guidance systems in various high-precision tasks across diverse industries.

Chapter 8

Impact and Future Direction

This thesis represents a comprehensive investigation into the design, implementation, and evaluation of interactive MR widgets for tool-to-target alignment (TOTTA) guidance in spatial environments. Through systematic research, innovative prototypes, and rigorous user evaluations, we have advanced virtual widgets' precision, usability, and cross-domain adaptability, targeting critical challenges in both the medical and industrial fields.

In **Chapter 2**, we defined the TOTTA guidance problem and established its relevance across multiple domains. A systematic review of 206 papers—narrowed to 24 deeply relevant works—revealed the fragmented nature of current widget designs and evaluation methods. This review laid the foundation for identifying key design gaps, such as lack of standardization, limited usability considerations, and poor scalability. These insights justified the development of new, modular, and user-centered widget solutions and a flexible evaluation framework. The findings from this review confirmed the pressing need for standardized yet adaptable methodologies in MR interaction design.

In **Chapter 3** reviewed key advancements in AR-assisted dental tool manipulation, highlighting significant improvements in accuracy through visual widget integration. While current systems demonstrate strong performance using static overlays, they often fail to support full 5DOF control and intuitive user interaction. Emerging dynamic widget designs show promise in addressing these limitations, suggesting a clear direction for future innovation. These insights lay the groundwork for developing more adaptive, user-friendly solutions, which were explored in the following chapters.

In **Chapter 4**, we introduced the Virtual Stigmometer Widget (ViSti)—a 5DOF tool manipulation solution for dental implantology. ViSti significantly outperformed existing golden standard widgets in user satisfaction, mental demand, and frustration, as evidenced by NASA-TLX evaluations. It also demonstrated the feasibility of sterile, touchless interaction in high-precision tasks. Despite challenges transitioning from 2D to 3D visualizations and limitations in physical effort, the ViSti design validated the core principles of ergonomic MR guidance and encouraged future improvements, including nonlinear gain functions and AR-based deployment.

Chapter 5 expanded on this foundation with the development of the Augmented Collimator Widget (ACW), which applied cognitive perception principles—particularly Gestalt reification—to enhance error visibility and angular precision. Through a controlled user study with 30 participants and 32 targets, ACW achieved notable improvements in angular (+47%) and positional (+19%) accuracy while reducing frustration and mental demand. While task time and physical demand increased, the results positioned ACW as a strong alternative to conventional approaches. The modular infrastructure used in Unity3D ensures flexibility and paves the way for continued refinements and cross-domain testing.

Chapter 6 emphasized co-design and modularity through the development of Dynamic Widgets (DWs) for MR-based drill tool manipulation. Engaging domain experts (dentists) and MR specialists led to superior designs with enhanced precision and overall user preference. Though trade-offs emerged regarding physical and mental effort, the iterative, human-centered design process validated the approach. These dynamic widgets demonstrated scalability and reusability, suggesting strong potential in broader manufacturing, assembly, and maintenance contexts.

The cumulative contributions of this thesis address long-standing challenges in MR-based tool manipulation: improving visual clarity, reducing user error, enhancing precision, and increasing user acceptance. Our novel widget designs—ViSti, ACW, and DWs—demonstrate how cognitive science, ergonomic design, and interactive technology can be merged to redefine precision interaction paradigms. These designs' modular and extensible nature supports adoption across domains, particularly in high-stakes environments such as surgery and industrial fabrication.

Our open-source, systematic evaluation framework is foundational to standardization in this evolving field. It enables consistent benchmarking of widget performance and promotes replicability and collaborative development across the research community.

Looking forward, this work suggests several promising research directions:

- Haptic Feedback Integration: Incorporating glove-based or wearable haptics to improve depth perception and interaction realism.
- Adaptive Interfaces: Leveraging real-time machine learning to dynamically adjust widget parameters to individual user behaviors and task complexities.
- Real-World Testing in AR/MR: Deploying these widgets in real setups with expert end-users to validate system effectiveness in situ and under operational constraints.
- Inclusivity and Accessibility: Expanding the design space to consider a broader range of user needs and physical abilities to foster versatile usability.

This thesis establishes a solid groundwork for the continued evolution of interactive MR widgets for precision tool manipulation. By introducing innovative designs, rigorous empirical validation, and a user-centered design approach, we have contributed meaningfully to both the academic discourse and practical application of MR systems in healthcare and industry.

As these technologies mature, their widespread adoption promises to elevate precision, safety, and efficiency standards in critical workflows. Ultimately, this work contributes to technological innovation and enhances human capability—empowering professionals across disciplines to perform confidently, accurately, and easily.