EFFECTS OF VIRTUAL REALITY FEEDBACK ON INDIRECT VISION PERFORMANCE IN MINIMALLY INVASIVE ENDODONTIC OPERATIONS

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ABSTRACT

Minimally invasive endodontic access cavity preparation is important for preserving tooth structure. Performing this procedure requires bimanual manipulation of both a dental mirror and a surgical instrument, and the mirror must be positioned correctly to enable indirect vision. Practicing these psychomotor skills can be challenging in traditional learning environments. Virtual reality (VR)-based simulation with haptic feedback provides a safe environment for trainees to practice such skills and enables the integration of guidance methodologies to support skill acquisition.

In this project, a VR-based dental simulation system was developed incorporating three guidance methodologies — visual, verbal, and haptic — to evaluate their effectiveness in comparison with each other and with the no-guidance condition. The evaluation focused on mirror handling performance, task execution performance, and user perception. A randomized 4x4 Latin square crossover design was conducted with 20 fourth-year dental students.

The results indicated that verbal guidance and the no-guidance condition generally resulted in better performance than visual and haptic guidance in both mirror handling and task execution although most metrics showed no statistically significant difference among the guidance conditions. The usability questionnaire results also showed that the no-guidance condition was perceived as having the highest system usability. Participants reported positive perceptions of verbal guidance, expressed mixed opinions about visual guidance, and generally found haptic guidance to be obstructive.

Overall, the findings suggest that although multimodal feedback is often expected to enhance learning, the additional complexity introduced by such feedback may hinder rather than support the learning process.

Keywords: Dental Education, Simulation, Virtual Reality, Psychomotor Skills, Learning Guidance, Haptic Feedback, Endodontics

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INTRODUCTION

1.1 MOTIVATION

Oral health is a fundamental component of overall health, and dentistry therefore represents a critical domain within modern healthcare. Many dental procedures require high levels of precision, fine motor control, and advanced psychomotor coordination. In particular, surgical endodontics demands accurate instrument manipulation within a confined intraoral space. Because direct vision is often obstructed, dentists must rely on indirect vision using a dental mirror. Effective mirror orientation is essential to ensure safe, accurate, and efficient treatment.

The acquisition of psychomotor skills is a central objective in dental education. Before treating patients independently, students must develop foundational competencies in diagnosis, instrument handling, and surgical procedures within controlled training environments.

Mirror-based operation requires refined hand-eye coordination, spatial awareness, and the ability to interpret reversed visual feedback. Correctly orienting the mirror so that the operative field is clearly visible constitutes one of the most complex psychomotor skills in dentistry, as it involves coordination under indirect vision within a limited working space. Traditionally, mirror orientation skills are taught through instructor-guided practice on mannequins, followed by supervised treatment of real patients. [15]. Furthermore, ergonomics plays a crucial role in dental practice. Correct posture and proper instrument handling are strongly associated with the prevention of musculoskeletal disorders among dental professionals [33]. Thus, mastering mirror orientation is not only important for procedural success but also for long-term occupational health.

While instructors can observe external movements and provide real-time verbal feedback, a critical limitation persists: they cannot directly perceive the operative field exactly as it appears to the trainee through the mirror. Consequently, instructors must infer the student's perceptual and cognitive processes indirectly, which may reduce the precision and effectiveness of feedback. This pedagogical constraint highlights the need for training systems that allow both objective performance measurement and controlled delivery of targeted guidance.

Simulation-based training has emerged as a powerful tool in healthcare education. Advances in computer graphics, real-time rendering, and interactive systems have enabled the development of highly realistic training environments. In educational contexts, simulations provide several advantages: they allow repeated practice without risk to patients, support standardized training scenarios, reduce material costs, and enable both real-time and post-session performance assessment.

In dental education, simulation-based systems have been widely investigated for their effectiveness in improving clinical skills [3, 25, 30]. These systems offer controlled learning environments in which trainees can develop procedural competencies prior to patient interaction. However, many existing platforms focus primarily on visual simulation, with varying levels of integration of multimodal feedback mechanisms.

Virtual reality (VR) further enhances simulation-based learning by providing immersive, three-dimensional environments typically accessed through head-mounted displays. VR enables users to interact with virtual objects in real time, fostering spatial presence and experiential learning. In dental training, VR-based simulators allow students to practice procedures within realistic operative scenarios while maintaining a safe and repeatable environment.

Empirical studies have demonstrated the utility of computer-based and VR simulators for skill acquisition in dentistry [26, 35]. These systems support experiential learning and may reduce anxiety associated with early clinical exposure. Nevertheless, immersion alone does not guarantee effective skill acquisition, and the design of instructional guidance within VR environments remains a critical factor.

Haptic technology introduces force feedback into digital environments, enabling users to perceive virtual objects through tactile and kinesthetic sensations. In surgical training contexts, haptic feedback contributes to realism by simulating resistance, texture, and contact forces. This sensory modality is particularly relevant in dentistry, where tactile perception plays a central role in procedural control.

Research in dental education has examined the effectiveness of visuo-haptic simulators for improving surgical skills [36]. Findings suggest that integrating haptic feedback and visually guiding a user can enhance motor learning by reinforcing sensorimotor coordination. However, the comparative impact of different guidance modalities-visual, verbal, and haptic-on specific psychomotor tasks such as mirror orientation remains insufficiently explored.

Instructional guidance is a well-established determinant of effective skill acquisition. In motor learning and technology-enhanced training, guidance can be delivered through multiple modalities, for example visual cues, verbal instructions, and haptic assistance. In some studies, multimodal guidance has been shown to improve execution performance and skill retention compared to unguided practice [7].

In immersive simulation environments, the integration of guidance strategies must be carefully designed to balance performance support and learner autonomy. Excessive guidance may hinder long-term retention, whereas insufficient feedback may impair initial skill acquisition. Despite growing interest in VR-based dental training, limited research has systematically compared different guidance modalities within a unified experimental framework, particularly for complex mirror-mediated tasks.

Although VR and haptic technologies have been increasingly incorporated into dental education, the relative effectiveness of different guidance modalities for training mirror orientation in surgical endodontics remains unclear. Existing studies often evaluate simulator effectiveness in general procedural contexts but do not isolate mirror-based psychomotor coordination as a distinct learning challenge. Furthermore, few investigations directly compare visual, verbal, and haptic guidance within the same experimental design.

In this project, we developed a VR-based simulation environment designed specifically to train mirror orientation during surgical endodontics. Three guidance modalities-visual guidance, verbal guidance, and haptic guidance-were implemented and compared against each other and no-guidance condition. A randomized crossover study design was employed to evaluate their relative effectiveness.

The evaluation considered objective performance metrics and system usability. By systematically examining how different guidance strategies influence skill acquisition in a controlled VR environment, this study aims to inform the design of evidence-based feedback mechanisms and systems to teach fine complex motor skills in preclinical endodontic training and contribute to the broader field of technology-enhanced medical education.

1.2 RESEARCH QUESTIONS

Our objective in this project was to study the effectiveness of the implemented guidance methods in the VR dental simulator. The main objectives were to compare the users' task execution performance, mirror orientation performance, and their perception of the system usability. Based on these objectives, the following research questions were formulated:

- *R1*: How effective was each guidance methodology in terms of mirror handling compared to the others and the no-guidance condition?
- *R2*: How effective was each guidance methodology in terms of task execution performance compared to the others and the no-guidance condition?
- *R3*: What was the users' perception of the system usability under each guidance condition?

Based on these research questions, the following hypotheses were formulated:

- *H1*: Users who used the system with guidance would perform better in terms of mirror handling than users who used the system without guidance.
- *H2*: Users of the system with guidance would perform better in task execution than users of the system without guidance.
- *H3*: Users would perceive the system with guidance as more usable than the system without guidance.

1.3 STRUCTURE OF THE THESIS

The structure of this thesis is as follows:

- Chapter 2 - Related Work: Presenting the previous works that were related to the field of the project.
- Chapter 3 - Algorithms and Methodology: Explaining the system design, and algorithm implementation.
- Chapter 4 - Implementation: Describing system implementation and the development tools.
- Chapter 5 - User Study: Describing the design of the user study as well as the data collection.
- Chapter 6 - Results: Presenting the result of the user study.
- Chapter 7 - Discussion: Discussing the findings, thesis strengths, limitations, and future work.
- Chapter 8 - Conclusion: Presenting the conclusion of the thesis.

2

RELATED WORK

This chapter presents a summary of previous research related to this study. It covers the following topics: simulation in dental education, psychomotor skill acquisition, haptics in dental education, visual guidance, verbal instruction and human-computer interaction, and haptic guidance.

2.1 SIMULATION IN DENTAL EDUCATION

The integration of simulation technologies into dental education has been widely examined in the literature. A substantial body of research suggests that simulation enhances learning effectiveness, improves psychomotor skill acquisition, and increases training efficiency in preclinical settings. Multiple reviews report that simulation-based training provides a structured and repeatable environment in which students can practice clinical procedures without risk to patients [22, 25, 32]. In particular, Perry et al. (2015) highlighted the cost-effectiveness of simulation for skill development [32], while Moussa et al. (2022), in a review of 52 studies, found consistent improvements in student learning outcomes associated with virtual technologies [25].

Beyond measurable learning outcomes, simulation has also been positively perceived by both students and educators. Buchanan (2001) noted that simulators allow trainees to complete mandatory refresher training independently and provide instructors with opportunities to review and adapt curricula according to students' needs [5]. Similarly, Moussa et al. (2022) reported positive perceptions of virtual technologies across all studies included in their review [25]. The ability of simulators to provide immediate feedback and enable self-directed practice has also been used to address faculty staffing challenges in preclinical courses [5]. As a result of these pedagogical and logistical advantages, simulation has been increasingly integrated into dental curricula over time [31].

Despite these benefits, several limitations must be considered. Higgins et al. (2020) identified a relative paucity of high-quality research examining the educational structure of dental and oral health simulation activities, despite the growing adoption of such technologies [13]. While simulators are considered effective tools for the acquisition and assessment of psychomotor skills, evidence regarding their broader educational impact remains limited. Additionally, Perry et al. (2015) pointed to practical barriers to integration, including high initial costs and limited content variability [32]. Li et al. (2021) further emphasized hardware constraints, arguing that current technological limitations prevent simulation from fully replacing traditional methods for primary skill acquisition [22]. Moreover, although virtual reality (VR)-based systems show promise, their integration into undergraduate curricula remains debated in terms of cost-effectiveness and pedagogical value [26, 35].

Given both the advantages and constraints of simulation technologies, several recommendations have been proposed for their effective integration into dental education. For psychomotor skill development, repetitive and deliberate practice is essential; therefore, simulation systems should be designed to support structured, repeated training sessions [12]. Feedback mechanisms are equally critical, as timely and constructive feedback has been shown to maximize learning benefits [26]. Furthermore, Li et al. (2021) suggested that future developments should explore the integration of artificial intelligence as individualized instructional support, as well as improvements in haptic feedback, video transmission, and system immersiveness [22].

From an instructional design perspective, Higgins et al. (2020) emphasized that simulation systems should be grounded in established educational theories [13]. They proposed a structured framework consisting of preparation, briefing, simulation, feedback, debriefing, reflection, and evaluation. Importantly, simulation should be implemented as a purpose-driven educational tool rather than as a universal replacement for traditional teaching methods [12]. When carefully aligned with pedagogical objectives, simulation can complement conventional instruction and enhance the overall effectiveness of dental education.

2.2 PSYCHOMOTOR SKILL ACQUISITION

Psychomotor skills are fundamental to performance in domains that require the integration of cognitive processing and coordinated motor execution, including medical and dental education [15, 17]. The literature on psychomotor skill acquisition consistently emphasizes the importance of structured, task-specific instruction, particularly during the early stages of training, where learners benefit from a supportive and low-pressure environment [17]. Historical and contemporary analyses of health professions education further indicate that the effective development of complex psychomotor competencies depends on clear instructional sequencing, guided practice, and the progressive integration of component skills [27].

To manage task complexity, instructional strategies such as part-task training have been widely advocated. This approach involves initially separating cognitive and motor components of a task to reduce cognitive load, followed by gradual reintegration as proficiency increases [9]. Evidence suggests that such structured decomposition can facilitate both motor execution and situational awareness. In addition, cross-domain research in areas such as sports, music, and healthcare highlights the importance of constructive feedback, demonstration, and active learner engagement in promoting skill acquisition [2].

However, despite generally positive findings, the empirical support for certain instructional techniques remains uneven. Variability in study design, outcome measures, and training contexts limits the generalizability of some conclusions. Consequently, further rigorous and context-specific research is needed to clarify which instructional strategies are most effective for developing psychomotor competence in dental education.

2.3 HAPTICS IN DENTAL EDUCATION

Haptic technology has been extensively investigated in dental education, particularly with respect to its potential to enhance psychomotor skill development and learner confidence. Several empirical studies suggest that visuo-haptic simulation systems can positively influence both objective performance and subjective learning experiences. For example, Samuel et al. (2024) examined the effectiveness of dynamic visual guidance within a haptic-enabled simulator for training in inferior alveolar nerve block procedures. Their findings indicated that students who trained with the simulator reported greater confidence during their first clinical injection, required fewer syringe readjustments, and achieved higher anesthetic success rates compared to those trained conventionally [36].

Similarly, Konukseven et al. (2010) developed a visuo-haptic dental simulation system that was evaluated by practicing dentists and received generally positive feedback regarding its usability and educational potential [19]. Osnes and Keelin (2017) introduced a haptic simulation for caries removal training that combined force feedback with visual segmentation of tooth structures, aiming to improve spatial understanding and tactile discrimination [29]. More recently, Rodrigues et al. (2023) evaluated a haptic dental simulator (DENTIFY) in a preclinical drilling task and reported improvements in student performance as well as reduced procedure time following simulator-based training [34].

The impact of haptic simulation on learner perception and training sequence has also been explored. Daud et al. (2023) compared two groups of dental students who alternated between VR haptic simulation and conventional preclinical training. Questionnaire results demonstrated strong agreement that the VR haptic system could effectively supplement traditional instruction [8]. Likewise, Serrano et al. (2023) assessed institutional perspectives on VR haptic trainers and reported high levels of satisfaction among dental schools, with many recommending broader adoption [37].

Systematic reviews further support these findings. Patil et al. (2023) concluded that haptic feedback devices can assist junior dental students in improving psychomotor skills, particularly by providing instantaneous feedback that enhances self-assessment and reduces subjective evaluation bias [30]. Bandiaky et al. (2024) similarly reported that haptic simulators significantly improve motor skill acquisition in preclinical settings and are generally well perceived by learners [3]. However, the effectiveness of haptic feedback may depend on how it is integrated with other instructional modalities. Al-Saud et al. (2017), for instance, compared device-based training, verbal instruction, and combined verbal-device training in a drilling task. Their results showed that the combined condition produced superior performance and fewer errors, suggesting that multimodal instructional approaches may yield greater benefits than haptic feedback alone [1].

Overall, the literature indicates that haptic simulation can enhance technical performance, learner confidence, and perceived educational value in dental training. Nevertheless, many studies rely on short-term performance metrics or subjective questionnaires, and evidence regarding long-term retention and transfer to clinical practice remains comparatively limited. Future research should therefore focus on rigorous, longitudinal evaluation of haptic technologies to determine their sustained educational impact.

2.4 VISUAL GUIDANCE

Visual guidance has been widely investigated as a strategy to enhance skill acquisition in simulation-based learning environments. Wierinck et al. (2005) examined the effectiveness of visual feedback in manual dexterity training during a dental drilling task. Participants were divided into three groups: training with visual feedback, training without visual feedback, and no training. Their findings indicated that participants who trained with visual feedback achieved higher immediate performance scores compared to the other groups. However, those who trained without feedback demonstrated superior performance in retention tests, suggesting that while visual feedback may enhance short-term performance, it may not necessarily promote long-term skill retention [38].

Similarly, Lam et al. (2016) investigated the use of visual guidance and performance metrics as assessment tools in a virtual phacoemulsification surgical simulator. Participants completed the four principal stages of cataract surgery within a virtual environment, where real-time feedback was provided and performance was automatically evaluated upon task completion. The results indicated that simulator-generated metrics showed potential for objective assessment of procedural competence. These findings support the broader role of visual guidance not only in training but also in performance evaluation within virtual surgical environments [20].

As interest in visual guidance has increased, a range of guiding techniques has been developed to improve gesture-based training. Jeanne et al. (2017) compared three visual guidance methods—feedforward guidance, concurrent orientation feedback, and error-based assistance for gesture guidance (EBAGG)—in a task requiring participants to reproduce time-based gestures in three-dimensional space. Their results demonstrated that the EBAGG method produced greater performance improvements during training compared to the other approaches [14].

Collectively, these studies suggest that visual guidance can enhance motor performance during simulation-based training. However, differences between immediate performance gains and long-term retention highlight the need for careful instructional design. The effectiveness of visual guidance may depend on how feedback is structured, when it is provided, and how it supports the development of independent motor control.

2.5 VERBAL INSTRUCTION AND HUMAN-COMPUTER INTERACTION

Verbal instruction remains one of the most commonly used instructional methods in traditional training environments. Within the field of human-computer interaction, several studies have examined its effectiveness in navigation and learning processes. For example, Yedidsion et al. (2019) evaluated the effectiveness of natural-language guidance delivered by multiple robots within a confined environment. By comparing multi-robot guidance, single-robot guidance, and no-robot conditions, the study found that the multi-robot system produced superior navigation performance. These findings suggest that distributed verbal instruction, when appropriately coordinated, can enhance task efficiency in complex environments [40].

Verbal instruction has also been examined in educational simulation contexts. Liu and Chuang (2011) explored how verbal instruction format and prior knowledge affected cognitive load and learning outcomes in an eighth-grade computer simulation setting. Students who received spoken instructions demonstrated improved performance compared to those who read on-screen text; however, they also reported higher cognitive load. This result indicates a potential trade-off between instructional effectiveness and cognitive processing demands, emphasizing the importance of aligning verbal guidance with learners' prior knowledge and cognitive capacity [23].

Finally, Ockey and Chukharev-Hudilainen (2021) compared a computer spoken dialogue system with human interlocutors in assessing interactional competence. While the computer system provided more standardized and consistent interactions, participants expressed a preference for human partners due to greater perceived naturalness. This contrast highlights an important distinction between procedural consistency and perceived authenticity in verbal instructional systems [28].

Collectively, these studies suggest that verbal instruction can effectively guide performance across navigational and educational domains. However, its impact appears to depend on contextual factors such as system design, learner characteristics, and the balance between standardization and natural interaction. Further research is therefore needed to determine how verbal guidance can be optimally integrated into simulation-based learning environments without imposing excessive cognitive load or reducing user engagement.

2.6 HAPTIC GUIDANCE

Haptic technology, which enables the delivery of force feedback to users, has been widely investigated as a means of enhancing motor skill acquisition in training environments. Several studies have examined how different forms of haptic guidance influence performance and retention. For example, Crespo and Reinkensmeyer (2008) evaluated haptic guidance strategies in a wheel-steering task analogous to vehicle control. Participants were assigned to no-guidance, fixed-guidance, or guidance-as-needed conditions. Their findings indicated that guidance-as-needed led to superior performance during practice compared to the other groups. However, with extended training, performance differences between groups diminished, suggesting that adaptive assistance may accelerate early learning but does not necessarily confer long-term advantages once sufficient practice is achieved [7].

Similarly, Forsyth and MacLean (2005) investigated predictive haptic guidance using a look-ahead algorithm in a steering task. When compared to unguided training and a standard potential-field method, predictive guidance produced superior quantitative performance and was also preferred subjectively by participants. These findings suggest that anticipatory or adaptive haptic strategies may enhance both task efficiency and user experience [11].

In contrast to assistive guidance, Lee and Choi (2010) explored the use of haptic disturbance as a training strategy in a target-tracking task. Four practice conditions were compared: no haptic feedback, progressive haptic guidance, repulsive disturbance, and noise-like disturbance. While progressive guidance resulted in the highest tracking accuracy during training, noise-like disturbance yielded better retention performance. This pattern aligns with motor learning principles suggesting that introducing variability or desirable difficulty may enhance long-term retention, even if immediate performance appears lower [21].

Bluteau et al. (2008) further differentiated between types of haptic feedback, comparing position-based and force-based feedback in a trajectory-following task. Their results indicated that force feedback improved movement fluency in visuomanual tracking [4]. However, not all findings uniformly support the superiority of haptic guidance. Liu et al. (2006), in a study comparing mechanical haptic guidance with visual demonstration alone during 3D path reproduction, found no significant difference in performance gains or retention between conditions [24].

Taken together, the literature suggests that haptic feedback can enhance motor performance, particularly during early training stages or when adaptive and predictive strategies are employed. However, its benefits for long-term retention are less consistent and may depend on how guidance is structured. Overly assistive feedback may risk dependency, whereas strategically introduced variability or disturbance may promote more durable learning. These findings highlight the importance of carefully designing haptic interventions to balance immediate performance support with long-term skill development.

2.7 MULTIMODAL FEEDBACK

The integration of visual and haptic guidance has been investigated as a multimodal approach to enhancing motor skill acquisition. Evidence suggests that combining sensory modalities may provide complementary information, thereby improving performance beyond what can be achieved through a single feedback channel. For example, Caccianiga et al. (2021) examined the role of feedback in a needle-driving task in which participants were required to guide a needle through a series of ring-shaped targets. Four training conditions were compared: no feedback, visual feedback only, haptic feedback only, and combined visual-haptic feedback. The results demonstrated that the presence of feedback significantly improved performance overall, with the combined visual-haptic condition leading to the greatest reduction in errors. These findings indicate that multimodal feedback may enhance precision in fine motor tasks [6].

Similarly, Feygin et al. (2002) investigated haptic guidance in a complex three-dimensional motion-tracking task. During training, participants received one of three guidance conditions: haptic-only, visual-only, or combined visual-haptic feedback. Performance was later evaluated under haptic-only and visual-haptic testing conditions using metrics such as positional accuracy, trajectory shape, timing, and drift. The results showed that participants trained with combined visual-haptic feedback performed better in the testing phase than those trained with haptic feedback alone, suggesting that multimodal guidance may facilitate more robust skill acquisition [10].

Collectively, these studies support the potential advantages of integrating visual and haptic feedback in motor training. By engaging multiple sensory pathways, multimodal guidance may enhance error detection, spatial awareness, and movement calibration. However, the degree to which combined feedback improves long-term retention, as opposed to immediate performance, remains an open question and warrants further investigation.

2.8 SUMMARY OF RELATED WORK

In summary, previous studies have found that computer simulations support skill acquisition in dental training. In addition, the integration of haptic technologies into simulations enhances both technical performance and learner confidence before executing tasks in real-world environments. Furthermore, the application of guidance methodologies in computer-based training programs has been shown to be beneficial for trainees.

However, although learning through computer-based simulations and the implementation of various guidance methodologies have been found to be effective across different fields, psychomotor skill acquisition requires context-specific designs. To date, no literature has addressed the effectiveness of such integration for fine psychomotor skill training, such as learning to adjust the dental mirror.

In this study, we not only investigate the effectiveness of integrating various guidance methodologies for mirror orientation in endodontic surgery simulations, but also compare these methodologies to determine which is most effective for fine psychomotor skill acquisition in dental endodontic procedures.

3

ALGORITHMS AND METHODOLOGY

This chapter presents the system design and methodologies. In addition, the algorithm in the development of the project is also given in the chapter.

3.1 SYSTEM DESIGN OVERVIEW

In the scope of this work, we developed a system that allows users to learn and practice mirror adjustment and manipulation for minimally invasive endodontic access cavity preparation tasks in a virtual reality environment. The system is a continuation of the dental simulator developed by Kaluschke et al. [16]. The dental simulator was originally developed to help dental students practice their skills in endodontic access cavity preparation tasks. The system provides haptic force feedback between the bur tool and the tooth, enabling a realistic training experience.

In addition, after users finish their performance in a session, the system provides a 3D animation replay of their performance along with a performance score. This allows users to review their performance and learn from their mistakes.

For this thesis, we implemented three mirror guidance feedback methods in the system, including visual guidance, verbal guidance, and haptic guidance. In addition, we implemented a posture correction system that notifies the user when an incorrect posture is detected.

Figure 3.1 illustrates the overall system data flow. The system flow can be summarized as follows. First, the user calibrates the world origin, saves the initial head position, and selects the guidance method. These reference values are stored and later used to calculate the current surgical tool position, head position, and mirror position relative to the world origin in the 3D space. The calculated positions, together with the initial head position, are then used to determine the current guidance condition. The detailed guidance conditions are described in a later section of this chapter.

Based on the determined guidance condition and the selected guidance method, the system applies the corresponding guidance feedback to the user. Simultaneously, the system calculates haptic feedback for the surgical tool by comparing the tool position with the tooth position in 3D space. At the same time, posture correctness is evaluated by comparing the current head position with the initial calibrated head position, and posture correction feedback is provided to the user when necessary.

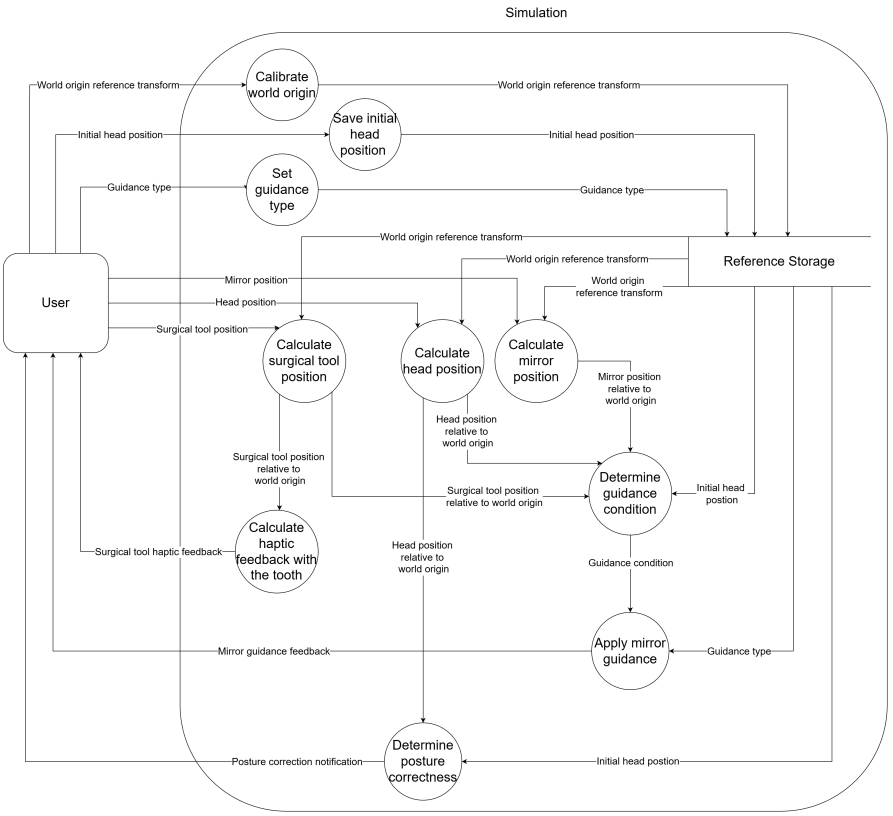

Figure 3.1: Overview of the system data flow

Furthermore, the system logs the user's actions, including head orientation and how the mirror and tool are held. These logs can be saved and replayed later. The log replay system allows both students and instructors to more easily identify mistakes, as it replicates the user's view during the trial.

Each guidance feedback method helps the user adjust the mirror so that the tooth becomes visible in the mirror. In the system, users can choose which guidance feedback they want to receive, or they can choose to use the system without any guidance.

Earlier in the development, we planned to utilize eye-tracking technology to give the feedback to users. However, later in the development of the project, we found that eye-tracking was unnecessary for mirror adjustment because the head position could be used for the calculation and the position of each eye could be an offset from the head. As a result, we did not incorporate the technology into the project.

3.2 POSTURE CORRECTION

This section describes the implementation of the posture correction notification in the simulation.

We implemented an algorithm that detects the user's posture and provides an audio notification when the user adopts an incorrect posture. The posture correction process is defined by six variables (see Figure 3.2 for visual illustration): initial head position (p_i), initial head forward vector (o_i), current head position (p), current head forward vector (o), head position threshold (d_{th}), and head orientation threshold (θ_{th}).

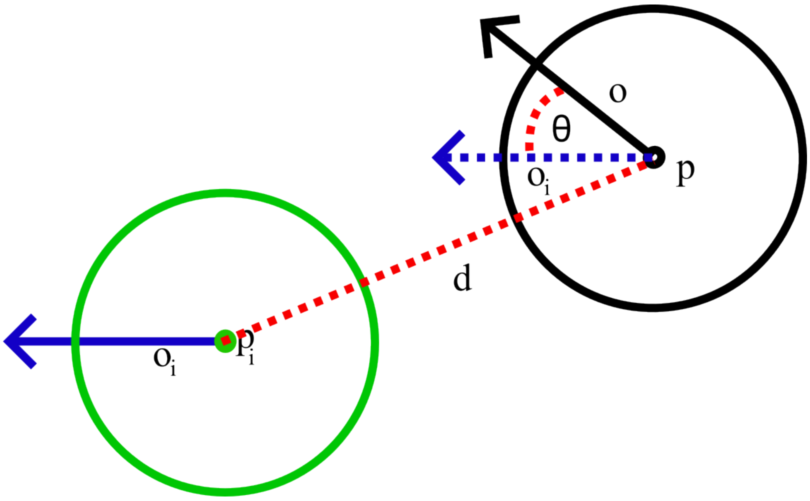

Figure 3.2: The visual illustration of posture correction components (d_{th} and θ_{th} are predefined). The green circle and the blue arrow represent the initial head location and forward direction. The black circle and arrow represent the current head location and forward direction.

We show the implementation of the posture correction process in Algorithm 1 [1]:

Algorithm 1 Posture Correction

```
$d \leftarrow$ distance between $p$ and $p_i$
$\theta \leftarrow$ angle between $o$ and $o_i$
if $(d > d_{th}) \vee (\theta > \theta_{th})$ then
    play the reminder sound
end if
```

The algorithm is described as follows:

1. The user assumes the correct posture either independently or based on the instructor's instructions.
2. The user calibrates the current posture.
3. A notification sound is played when one of the following conditions is met:
    - When the difference between the current head location and the calibrated head location exceeds a predefined distance threshold.

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[1] See Figure A.1 for visual diagram

- When the angular difference between the current head orientation and the calibrated head orientation exceeds a predefined angular threshold.

3.3 MIRROR CORRECTION

This section describes the algorithm for the mirror correction when one of the following conditions is met: the mirror is outside of the optimal area, the mirror is incorrectly oriented, and the mirror view was occluded by the head of the surgical tool. Figure 3.3 shows visual representation of each condition.

(a) Optimal area (b) Mirror orientation (c) Tooth occlusion

Figure 3.3: Mirror conditions representation

In general, all mirror guidance methods were implemented with the same goal: guiding the user to adjust the mirror so that the tip of the tooth, where the bur touches the tooth, remains visible in the mirror while the bur tool touches the tooth. All guidance methods share three conditions for applying guidance. The differences between the guidance methods lie in how they guide the user under each condition.

3.3.1 *Condition 1 - The Mirror is Located Outside the Optimal Area*

The optimal area refers to the region where the mirror should ideally be positioned. A 2D-visual representation of this area is shown in Figure 3.4. The highlighted region represents the optimal area.

The optimal area is represented as a region inside a cone and is defined by five variables: cone origin (o), cone direction (d), cone angle (θ), inner radius (r_1), and outer radius (r_2).

To determine whether the mirror is inside the optimal area, we implemented Algorithm 2 and describe it as follows[2]:

1. Let the point p represent the mirror position in 3D space.
2. Calculate the unit vector d_p pointing from o to p.
3. Calculate the angle θ_p between d and d_p.

---

[2] See Figure A.2 for visual diagram and Appendix A.2.1 for more detail

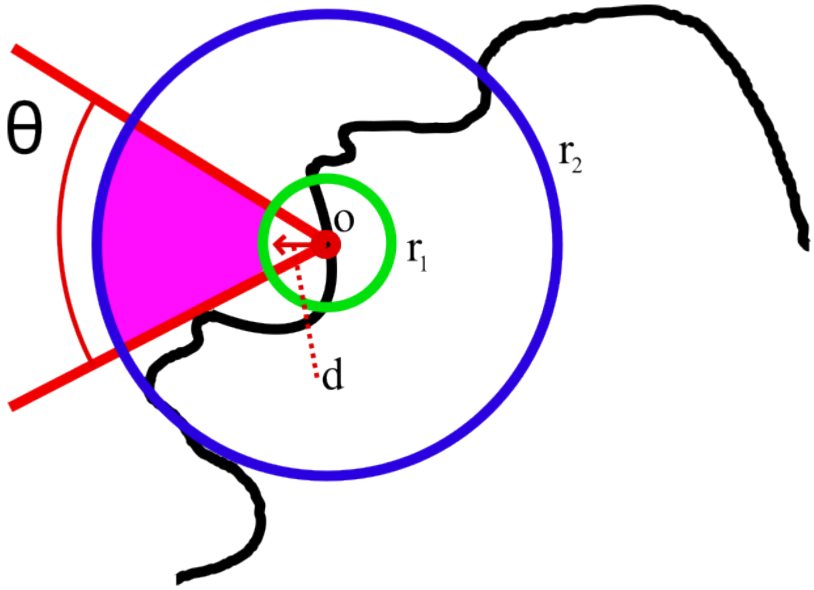


Figure 3.4: Visual representation of the optimal area. The pink area inside the cone represents the optimal area where the mirror should be.

4. **If** $\theta_p < \frac{\theta}{2}$ **and** the distance between p and o lies between r_1 and r_2, **then** the mirror is inside the optimal area.

Algorithm 2 Is a Point Inside the Optimal Area

```
$p \leftarrow$ mirror position
$d_p \leftarrow$ direction from $o$ to $p$
$\theta_p \leftarrow$ angle difference between $d$ and $d_p$
if $(\theta_p < \frac{\theta}{2}) \wedge (r_1 < |p - o| < r_2)$ then
    mirror is inside the optimal area
else
    mirror is outside the optimal area
end if
```

3.3.2 *Condition 2 - Mirror is Inside the Optimal Area but Incorrectly Oriented*

In this condition, the mirror is located inside the optimal area but is oriented incorrectly such that the reflection does not direct the tooth image toward the user's eyes.

The following variables are considered: head position (p_h), left eye position (p_{le}), right eye position (p_{re}), mirror position (p_m), mirror normal (n_m), tooth position (p_t), base angular threshold (θ_{th}), and distance adjustment stiffness (d_{ad})

We developed Algorithm 3[3] to determine the correctness of the mirror orientation.

---

[3] See Figure A.3 for diagram visualization

Algorithm 3 Is Mirror Correctly Oriented

```
$d \leftarrow$ distance between $p_t$ and $p_m$
$\theta'_{th} \leftarrow \theta_{th} - (d_{ad} \times d)$
$r \leftarrow$ reflection from $p_t$ on $p_m$ with the normal $n_m$
$t_h \leftarrow$ direction from $p_m$ to $p_h$
$t_{le} \leftarrow$ direction from $p_m$ to $p_{le}$
$t_{re} \leftarrow$ direction from $p_m$ to $p_{re}$
$\theta_h \leftarrow$ angle between $r$ to $t_h$
$\theta_{le} \leftarrow$ angle between $r$ to $t_{le}$
$\theta_{re} \leftarrow$ angle between $r$ to $t_{re}$
if $(\theta_h < \theta_{le}) \wedge (\theta_h < \theta_{re})$ then
    $\theta \leftarrow \theta_h$
else if $\theta_{le} < \theta_{re}$ then
    $\theta \leftarrow \theta_{le}$
else
    $\theta \leftarrow \theta_{re}$
end if
if $\theta > \theta'_{th}$ then
    The tooth is not visible on the mirror
end if
```

The algorithm is described as follows:

1. Compute the distance d between p_t and p_m.
2. Adjust the threshold θ'_{th} based on the base threshold θ_{th} and the distance d. As the mirror moves farther from the tooth, the observable angular range of the tooth tip decreases. Therefore, the angle threshold must be reduced accordingly. Figure 3.5 illustrates the visibility cone of the tooth tip in the mirror. The angular cone becomes narrower as the mirror distance increases $(\theta_1 > \theta_2)$.
3. Compute the reflection vector r using p_t as the source, p_m as the reflection point, and n_m as the reflection normal[4].
4. Compute the following normalized target vectors:
    - the target vector from the mirror to the head position (t_h)
    - the target vector from the mirror to the left eye (t_{le})
    - the target vector from the mirror to the right eye (t_{re})
5. Compute the angle θ between the reflection vector r and each target vector.
6. If the smallest θ exceeds θ'_{th}, the tooth is not visible in the mirror.

---

[4] See Appendix A.2.2

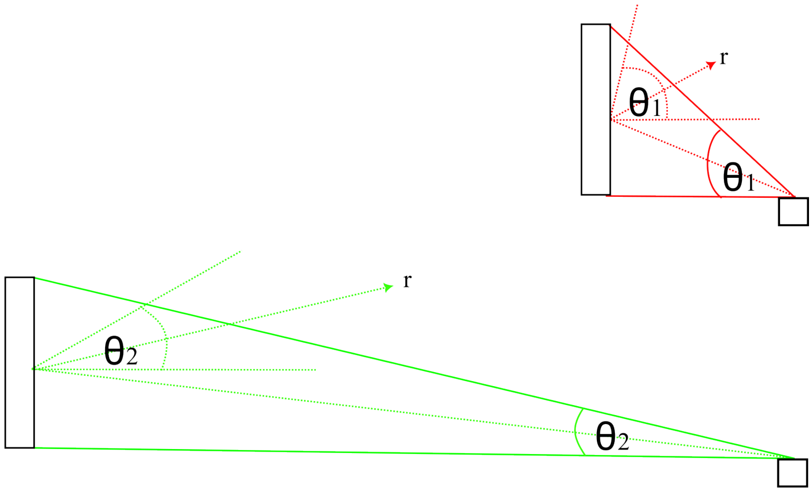


Figure 3.5: Angular threshold regarding the distance between the mirror and the tooth. The red cone illustrates the wider visibility angle when the mirror is closed to the tooth, while the green cone represents the narrower visibility angle as the mirror moves farther from the tooth.

3.3.3 *Condition 3 - Tooth is Occluded by the Bur Tool*

In this condition, the mirror is correctly positioned and oriented, but the view of the tooth is blocked by the bur tool.

The following variables are used: tooth tip position (p_t), bur head position (p_b), bur head radius (r_b),and mirror position (p_m).

We developed the occlusion detection algorithm as shown in the pseudocode in Algorithm 4[5]. The algorithm is described as follows:

1. Compute the line l_{tm} from p_t to p_m.
2. Compute the line l_{tb} from p_t to p_b.
3. Compute the projection parameter t corresponding to the closest point on the line segment l_{tm} to p_b.

   The point on the line can be expressed as

   $$p(t) = p_t + t \times l_{tm}.$$

   Since the vector from $p(t)$ to p_b is orthogonal to l_{tm} at the closest point,

   $$l_{tm} \cdot (p_b - p(t)) = 0.$$

   Substituting $p(t)$ gives

   $$l_{tm} \cdot (p_b - p_t - t \times l_{tm}) = 0,$$

---

[5] See Figure A.4 for visualization

which simplifies to

$$l_{tm} \cdot l_{tb} - t \times |l_{tm}|^2 = 0.$$

Therefore,

$$t = \frac{l_{tm} \cdot l_{tb}}{|l_{tm}|^2}, \quad t \in [0,1].$$

4. Compute the closest point on the line segment:

$$p_l = p_t + t \times l_{tm}.$$

5. Compute the distance d_{bl} between p_b and p_l.

6. If $d_{bl} \leq r_b$, the view is occluded; otherwise, the view is not occluded.

Algorithm 4 Is View Occluded

```
$l_{tm} \leftarrow$ line from $p_t$ to $p_m$
$l_{tb} \leftarrow$ line from $p_t$ to $p_b$
$t \leftarrow \frac{l_{tm} \cdot l_{tb}}{|l_{tm}|^2}, \quad t \in [0,1]$
$p_l \leftarrow p_t + t \times l_{tm}$
$d_{bl} \leftarrow$ distance between $p_b$ and $p_l$
if $d_{bl} \leq r_b$ then
    view is occluded
end if
```

When the view was occluded, we calculated the suggested mirror position p'_m, where the tip of the tooth was not occluded, using Algorithm 5[6]. The illustration is shown in Figure 3.6.

Algorithm 5 Find the New Mirror Position

```
$tangent_{len} \leftarrow \sqrt{|l_{tb}|^2 - r_b^2}$
$\theta \leftarrow \arctan2(r_b, tangent_{len})$
$per \leftarrow$ normalized perpendicular vector of $l_{tb}$ to $l_{tm}$
$dir_1 \leftarrow$ rotate $l_{tb}$ in $\theta$ angle toward the $per$ direction
$dir_2 \leftarrow$ rotate $l_{tb}$ in $\theta$ angle away from the $per$ direction
$tangent_{dir} \leftarrow$ normalized $dir_1$ or $dir_2$ that is more align with $l_{tm}$
$p'_m \leftarrow p_t + |l_{tm}| \times tangent_{dir}$
```

We describe the algorithm as follows:

1. Calculate the tangent lines between the position of the tooth tip and the head of the surgical handpiece.

2. The suggested mirror position p'_m was determined based on the following conditions:

---

[6] See Figure A.5 for visualization and Appendix A.2.4 for more detail

- p'_m lies on one of the calculated tangent lines.
- The selected tangent line l' is the line with the smallest angle relative to line l.
- The distance between p'_m (on l') and p_t is equal to the distance between p_m and p_t.

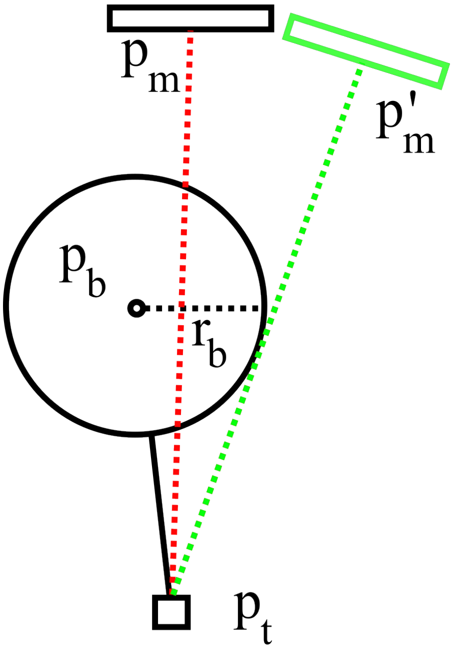


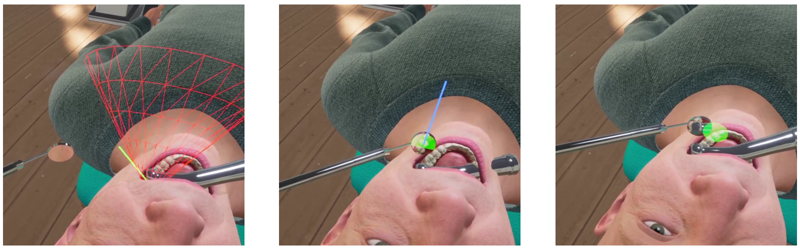
Figure 3.6: Suggested mirror location when the mirror view is occluded. The black rectangle shows the current mirror location. The red dotted line represents the line of sight from the tooth to the mirror, which is blocked by the bur tool. The green rectangle represents the new mirror location where the line of sight is not occluded.

3.4 GUIDANCE METHODOLOGIES

This section describes the implementation of three guidance methodologies that were developed.

3.4.1 *Visual Guidance*

Visual guidance consists of three components: the ghost mirror, the reflection line, and the cone visualization. The representation of each component is shown in Figure 3.7. Figure 3.7a shows the visualization of the cone, which represents the optimal area described in the previous section. In addition, the visual line in Figure 3.7b indicates the reflection vector of the tooth in the mirror. The line helps the user understand how to orient the mirror such that the tooth becomes visible. Lastly, the green object in Figure 3.7c is a ghost mirror. The



(a) Visual cone (b) Visual line (c) Ghost mirror

Figure 3.7: Visual guidance representation

ghost mirror is located where the mirror needs to be placed so that the tooth is not occluded.

The ghost mirror represented the ideal state of the mirror. When the ghost mirror appeared, the user was expected to move the mirror to the ghost mirror's position and rotate it such that the mirror aligned with the ghost mirror. To determine the orientation of the ghost mirror such that the tooth position would appear in the mirror reflection, we implemented Algorithm 6[7]:

For the ghost mirror orientation algorithm, the following variables are considered: tooth position (p_t), head position (p_h), ghost mirror position (p_m), ghost mirror normal (n_m), and ghost mirror rotation (r_m)

Algorithm 6 Ghost Mirror Orientation

```
$r \leftarrow$ reflection from $p_t$ on $p_m$ with the normal $n_m$
$t \leftarrow$ direction from $p_m$ to $p_h$
$\theta_{xy} \leftarrow$ signed angle between $t_{xy}$ and $r_{xy}$.
$\theta_{xz} \leftarrow$ signed angle between $t_{xz}$ and $r_{xz}$.
rotate pitch $\theta_{xz}$ and rotate yaw $\theta_{xy}$ on $r_m$
```

The algorithm is described as follows:

1. Calculate the reflection vector r using the tooth position as the source location, the ghost mirror position as the reflection point, and the ghost mirror normal as the reflection normal [8].

2. Compute a normalized target vector t that points from the ghost mirror position toward the user's head position.

3. Decompose the reflection vector r and the target vector t into the following two-dimensional vectors, producing r_{xy}, r_{xz}, t_{xy}, and t_{xz}.

4. Calculate the signed angular difference between each corresponding pair of two-dimensional vectors:
    - θ_{xy} is the signed angle between t_{xy} and r_{xy}.

---

[7] See Appendix A.2.5 for further details

[8] See Appendix A.2.2 for implementation details

  - θ_{xz} is the signed angle between t_{xz} and r_{xz}.

5. Add θ_{xz} to the pitch rotation and add θ_{xy} to the yaw rotation, while leaving the roll rotation unchanged.

A similar implementation of a ghost tool was found to be useful by Samuel et al. in helping students practice clinical skills [36]. The system adjusted the opacity of the ghost mirror according to the positional and orientation differences between the real mirror and the ghost mirror. Initial testing indicated that the ghost mirror was effective in guiding users toward the general mirror position and orientation.

However, further testing revealed that the ghost mirror alone was not sufficiently effective for fine-grained orientation adjustments. In some cases, the mirror appeared to be aligned with the ghost mirror from the user's perspective, yet the user was still unable to see the tooth reflection. To address this limitation, we implemented the reflection line. As the name suggests, the reflection line visualizes the reflection vector originating from the tooth and reflected by the mirror. By orienting the mirror such that the reflection line points toward the user's head, the reflection of the tooth becomes visible in the mirror. To minimize visual distraction while providing effective feedback, the opacity of the reflection line was dynamically adjusted, decreasing as the reflection vector aligned more closely with the direction toward the user's head.

Finally, when the mirror was positioned outside the optimal area, a cone was visualized. This cone served as a visual cue indicating that the user should move the mirror back inside the designated region.

Based on the conditions described in the previous section, the visual guidance feedback was applied as follows:

- **Condition 1:** The area cone was visualized to notify the user to move the mirror back inside the cone.
- **Condition 2:** The ghost mirror and the reflection line were displayed at the current mirror location.
- **Condition 3:** The ghost mirror became visible at the suggested mirror location described in the previous section.

Earlier in the implementation, several ideas and implementations were implemented but later dismissed. The first implementation to mention was the ghost mirror representation. In the first version, the ghost mirror had a handle similar to the dental mirror shown in Figure 3.8. However, since the mirror surface is flat, there are multiple ways to hold the mirror, and the way the ghost mirror suggested was only one of the ways, which might not be in a comfortable position for the user to hold. Without any positive effect and possibly being a visual obstruction, the handle was removed from the ghost mirror. Another idea that was dismissed was the representation of the ghost mirror when the tooth view was occluded. Initially, when the mirror view was occluded by the bur head, the ghost mirror blinked (switched visibility in a short period of time). However, this implementation was reported to be a distraction by the tester. As a result, the idea was dismissed.

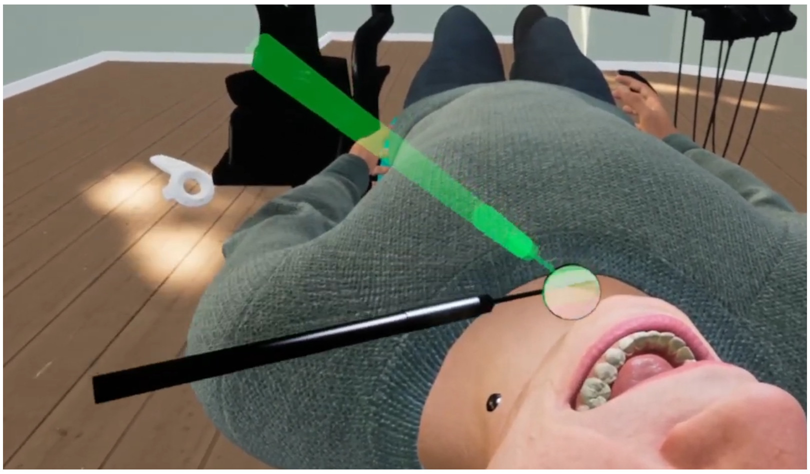


Figure 3.8: Initial representation of the ghost mirror

3.4.2 *Verbal Guidance*

The concept of verbal guidance was based on the assumption that the target users—dental students—already possessed the knowledge required to adjust the mirror, and therefore only needed to be notified when an adjustment was necessary. We implemented verbal guidance in a manner similar to the posture correction system. When one of the conditions described in the previous section was met, one of the following prerecorded audio message was played:

- **Condition 1:** The message "move mirror to the mouth" was played.
- **Condition 2:** The message "adjust mirror" was played.
- **Condition 3:** The message "tool tip is not visible" was played.

In the early implementation, the planned audio guidance was intended to be more descriptive. For example, if the ideal mirror position was 5 centimeters higher and 2 centimeters to the left of the current mirror position, the system would play the message "move mirror up 5 centimeters and left 2 centimeters". However, during testing, this approach was perceived as overly lengthy. In many cases, the audio message continued playing even after the user had already moved the mirror to the designated location. As a result, the feedback did not keep pace with the user's actions and imposed additional cognitive load on the user.

To address these issues, an expert recommended making the guidance more concise. Since the target users were students with prior knowledge of bimanual mirror adjustment, it was reasonable to assume that they already had a general understanding of how to adjust the mirror. Consequently, we implemented shorter and simpler audio cues in the final implementation.

3.4.3 *Haptic Guidance*

Haptic guidance uses force feedback from the haptic device to guide the user's hand to the desired location. For each previously described condition, the guidance behaved as follows:

- **Condition 1:** A force is applied toward the optimal area to guide the mirror into the correct region.
- **Condition 2:** If the mirror deviates significantly from the previous correct position, a force directs the mirror back to that position. If the positional difference is small but the orientation is incorrect, haptic noise is applied to prompt mirror adjustment.
- **Condition 3:** A direct force guides the mirror toward the suggested mirror position calculated to avoid occlusion.

One of the related studies found that haptic direct force was found helpful in immediate skills acquisition, and haptic noise was found useful in retaining the skill gained [21]. The haptic direct force magnitude (m) was calculated by the following equation:

$$m = \sqrt{\sum (p_i - p_i')^2} \times k, \quad m \in [0, 1]$$

where p is the mirror position, p' is the mirror target position, and k is a predefined stiffness.

Initially, the implementation of the haptic feedback differed for the condition in which the mirror was oriented incorrectly. At first, we calculated the final position for the haptic mirror that would produce a reflection toward the position of the tooth for the user. Algorithm 7[9] shows the computation of the final position.

We consider the following variables: tooth position (p_t), head position (p_h), mirror position (p_m), mirror normal (n_m), step size (s), and array of possible directions to move p_m (D).

We describe the algorithm as follows:

1. Let the current mirror position be p, the angular difference between the target vector and the reflection vector described in the previous section be θ, a predefined step size be s, and the target vector be t, which points from the mirror toward the head.

---

[9] See Appendix A.2.6 for further details

2. Calculate the new position p' as follows:
    - For each direction originating from point p, generate temporary positions p_i such that the distance between p and each p_i is s.
    - Compute the reflection vector r_i from each p_i using the tooth position as the source location, p_i as the reflection point, and the mirror normal as the reflection normal[10].
    - Calculate the angular difference θ_i between r_i and t.
    - Select p' as the p_i that yields the smallest value of θ_i.
3. Apply a haptic force to the mirror haptic device in the direction from p toward p'.

Algorithm 7 Direct Haptic Position Calculation

```
$r \leftarrow$ reflection from $p_t$ on $p_m$ with the normal $n_m$
$t \leftarrow$ direction from $p_m$ to $p_h$
$\theta \leftarrow$ angle between $r$ and $t$
$\theta_{min} \leftarrow \infty$
for $d_i \in D$ do
    $p_i \leftarrow p_m + d_i \times s$
    $r_i \leftarrow$ reflection from $p_t$ at $p_i$ with the normal $n_m$
    $\theta_i \leftarrow$ angle between $r_i$ and $t$
    if $\theta_i < \theta_{min}$ then
        $p'_m \leftarrow p_i$
        $\theta_{min} \leftarrow \theta_i$
    end if
end for
Move mirror toward $p'_m$
```

After testing this implementation, we observed that although users were able to see the tooth position through the mirror reflection, the resulting mirror position was sometimes uncomfortable and unnatural for them to hold.

Another method was implemented but not used in the final version. In this approach, when the mirror was oriented incorrectly, noise was applied to the mirror as a form of feedback. However, we found that providing only noise feedback did not give users sufficient guidance on how to correct the mirror orientation. Consequently, the final system combined direct force feedback with noise feedback when the mirror was oriented incorrectly.

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[10] See Appendix A.2.2 for implementation details

4

IMPLEMENTATION

This chapter describes the implementation of the system described in the previous section. An overview of each component, including both hardware and software, is provided in the later parts of this chapter.

4.1 HARDWARE

This section describes the hardware components that were used in the project development.

Three main components were essential for the development of the project: a desktop computer, a virtual reality head-mounted display (HMD), and two haptic devices. The specifications of the desktop computer used for development were as follows:

- CPU: Intel(R) Core(TM) i7-9800X CPU @ 3.80 GHz
- RAM: 64 GB
- GPUs: NVIDIA GeForce RTX 2080 SUPER with 8 GB of VRAM and NVIDIA GeForce RTX 2070 with 8 GB of VRAM

A key requirement for the desktop computers was the installation of two graphics cards. The base software was designed such that one GPU was dedicated to rendering while the other was used for simulation and feedback calculations [16]. In general, the system does not require a high-specification computer. However, depending on the HMD used, the PC specifications may need to be adjusted in order to fully utilize the capabilities of the device.

Two HMDs were used in this project. The first was the HTC Vive Pro Eye HMD, which provides a combined resolution of 2880 × 1600. The second was the Vive Focus Vision. This HMD is newer than the HTC Vive Pro Eye and offers a higher resolution, with the ability to display 3072 × 3072 pixels per eye at a 90 Hz refresh rate. Both HMDs include integrated eye-tracking capabilities.

The virtual dental handpiece and mirror were operated using two GeoMagic Touch haptic devices (Phantom), which provide six degrees of freedom (DOF) input and three DOF output. These devices deliver haptic feedback that simulates the tactile interaction between the handpiece and the virtual tooth, while also guiding the mirror toward the correct position.

4.2 SOFTWARE

This section describes the software that was used in the project development.

4.2.1 *Unreal Engine*

Unreal Engine[1] is a 3D computer graphics game engine developed by Epic Games. The engine is widely known for its capability to create highly realistic virtual environments. Unreal Engine supports development using the C++ programming language and also provides a graphical scripting system called "Blueprint", which enables developers to implement prototypes and simple logic more efficiently.

In addition to being one of the most widely used game engines in the industry, Epic Games provides access to the engine's source code for developers who wish to customize or extend its functionality.

Two versions of Unreal Engine were used during the development of the system. The first was a customized source build of Unreal Engine 4.27. The customization added a zoom functionality to the system, replicating the use of a magnifying device during surgical procedures. we used Unreal Engine 4.27 for development of the software for the HTC Vive Pro Eye. To run the system in VR, the SteamVR plugin was required, while the SRAnipal plugin was necessary for implementing eye-tracking functionality.

Later in the development process, after receiving the Vive Focus Vision headset, we changed the engine to a customized version of Unreal Engine 5.3 that also included the zoom functionality. This change was necessary because the eye-tracking functionality of the new HMD required the Vive OpenXR plugin, which was only available in newer versions of the engine.

4.2.2 *Visual Studio*

Visual Studio (VS)[2] is an integrated development environment (IDE) developed by Microsoft. The software supports various aspects of the software development process, including code editing, debugging, and compilation.

Visual Studio is the recommended IDE for working with Unreal Engine on Windows systems. In this project, Visual Studio 2022 was used. However, Visual Studio 2019 is also compatible with the Unreal Engine versions used in this project.

Several components needed to be installed within Visual Studio. Four primary workloads were required: *".NET Desktop Development"*, *"Desktop Development with C++"*, *"Windows Application Development"*,

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[1] https://www.unrealengine.com

[2] https://visualstudio.microsoft.com

and "*Game Development with C++*". In addition, the custom Unreal Engine version required the installation of the *Windows 10 SDK*, which was installed through Visual Studio.

4.2.3 *Software for the HMD*

To run the simulation in a VR environment, several software components were required depending on the HMD used. Both HMDs required SteamVR[3] in order to run the simulation in a VR environment. SteamVR is Valve's virtual reality platform that acts as a bridge between VR hardware and software, providing a universal environment in which different VR headsets and controllers can run VR applications.

The HTC Vive Pro Eye required "VIVE Console for SteamVR"[4] in order to utilize its eye-tracking functionality. This software provides options for managing and optimizing the headset and serves as the main configuration tool for the device. Additionally, the software package includes several development tools, including SRAnipal, which is required for implementing eye-tracking functionality on the HTC Vive Pro Eye.

For the Vive Focus Vision headset, in addition to SteamVR, the system required "Vive Hub"[5]. Vive Hub is a software platform used to connect newer Vive HMD models, such as the Vive Focus Vision and Vive XR Elite, to a PC. It enables the connection between the headset and the computer and allows users to configure headset streaming settings such as display quality. The software works together with SteamVR to stream PCVR applications to the headset.

4.2.4 *CUDA Toolkit*

The CUDA Toolkit[6] is NVIDIA's development platform for GPU-accelerated computing. It provides the tools, libraries, and APIs required to utilize the parallel processing capabilities of CUDA-enabled GPUs.

As described in previous sections, two graphics cards were used in this project. The CUDA Toolkit was required to manage the distribution of computational tasks across the GPUs.

4.2.5 *Haptic Device Driver*

To enable the use of the haptic devices, the software packages *OpenHaptics for Windows Developer Edition v3.5* and *Phantom Device Driver*

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[3] https://store.steampowered.com/app/250820/SteamVR

[4] https://store.steampowered.com/app/1635730/VIVE_Console_for_SteamVR

[5] https://www.vive.com/de/vive-hub/download

[6] https://developer.nvidia.com/cuda/toolkit

v5.1.7, provided by “3D Systems”[7], were required. These drivers enable communication between the Phantom haptic devices and the system.

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[7] https://www.3dsystems.com

5

USER STUDY

This chapter describes the user study that was conducted. It provides an overview of the study, as well as information about the samples, the study methodology, and the data collected.

5.1 OVERVIEW

In this study, we conducted a randomized crossover trial to investigate how training mirror orientation using different guidance modalities in a virtual reality environment for minimally invasive endodontic access cavity preparation affected mirror handling performance, task execution outcomes, and user perception.

Each guidance modality was evaluated and compared with the other modalities, as well as with a training condition in which no guidance was provided.

Initially, the Vive Focus Vision headset was planned for use in the user study. However, after experts who participated in the pre-study tested the HMD, they preferred the HTC Vive Pro Eye over the Vive Focus Vision. They reported that the image quality of the HTC Vive Pro Eye was clearer, whereas the Vive Focus Vision appeared blurrier. Therefore, the HTC Vive Pro Eye was selected for the user study.

In addition, we planned to conduct a long-term user study where each participant practiced performing the task with an assigned guidance methodology for several sessions over a period of time. Then, have them perform the task without guidance given to measure skills gained and retention. However, due to the limited number of participants available, we changed the study method to a randomized crossover trial instead. Furthermore, due to the same reason, the combination of guidance methodologies was initially considered to be included as one of the study conditions but later dismissed.

The desktop computer used for the user study had the following specifications:

- CPU: Intel(R) Core(TM) i9-10980XE CPU @ 3.00 GHz
- RAM: 128 GB
- GPUs: NVIDIA GeForce RTX 4090 with 24 GB of VRAM and NVIDIA GeForce RTX 3090 with 24 GB of VRAM

5.2 POPULATION AND SAMPLE

The participants in this study were fourth-year undergraduate dental students from the Faculty of Dentistry at Thammasat University in Thailand. To be eligible for participation, students were required to have completed the Endodontic course offered by the Faculty of Dentistry at Thammasat University. This requirement ensured that participants had a fundamental understanding of the procedure involved in the operation.

In addition, participants must not have had prior experience with the VR dental simulator described in [16]. Since the system used in this study was developed based on this simulator, prior experience could influence participant performance due to familiarity with the system.

Sample size was calculated using G*Power version 3.1.9.2 with the following assumptions:

- Significant Level (α): 0.05
- Statistical Power (1 - β): 0.80
- Effect Size: Medium Effect Size (Cohen's f = 0.25)
- Correlation among repeated measures: Moderate

Based on these assumptions, a total sample size of 20 participants was considered sufficient to detect statistically significant differences among the guidance conditions.

Participation in the study was voluntary. Participants were selected based on the order in which they applied to participate. If more than 20 students applied, additional applicants were placed on a waiting list and were contacted if any participants withdrew from the study.

Participants were recruited through several methods. One approach involved sending an email to all fourth-year dental students that included a recruitment flyer inviting them to participate in the study. Additionally, recruitment flyers were posted on the notice board at the dental student clinic. Students who were interested in participating could contact the researcher to assess their eligibility.

5.3 STUDY METHODOLOGY

When participants applied to participate in the study, they were randomly assigned to one of four groups. Each group had the opportunity to experience all feedback guidance modalities during the experiment. The difference between the groups was the order in which the feedback guidance modalities were presented (Table 5.1). The assignments were based on a Williams design [39] to ensure balanced exposure to all feedback conditions and to control for potential period and sequence effects.

Figure 5.1: User study environment

Each participant took part in the experiment over four separate days, with a 48-hour washout period between sessions. On each day, the participant performed a conservative access cavity preparation task in a VR dental simulator under one of four guidance conditions: visual guidance, verbal guidance, haptic guidance, or no guidance. Each research session lasted one hour per day, from 4:30 p.m. to 5:30 p.m., and was conducted at the preclinical endodontics laboratory at the Faculty of Dentistry, Thammasat University. A detailed explanation of each guidance modality is provided in a previous section of this chapter. The order in which the guidance modalities were presented differed depending on the group to which the participant was initially assigned. By the end of the study, all participants had experienced all four guidance conditions.

	Day 1	Day 2	Day 3	Day 4
Group 1	verbal	visual	haptic	no guidance
Group 2	visual	haptic	no guidance	verbal
Group 3	haptic	no guidance	verbal	visual
Group 4	no guidance	verbal	visual	haptic

Table 5.1: Sequence of guidance methods received by each participant group

Before the beginning of the first session, participants were provided with an informed consent form. The form informed them about their rights as research participants and the procedures involved in the study. After signing the consent form, the researcher explained the study procedure and described in detail how each guidance modality functioned.

After completing each session, the evaluation metrics and outcome scores related to the access cavity preparation performance were automatically recorded by the system. In addition, participants were required to complete a user satisfaction questionnaire and gave their opinion on the system that they tried. Figure 5.2 illustrates the flow of the user study.

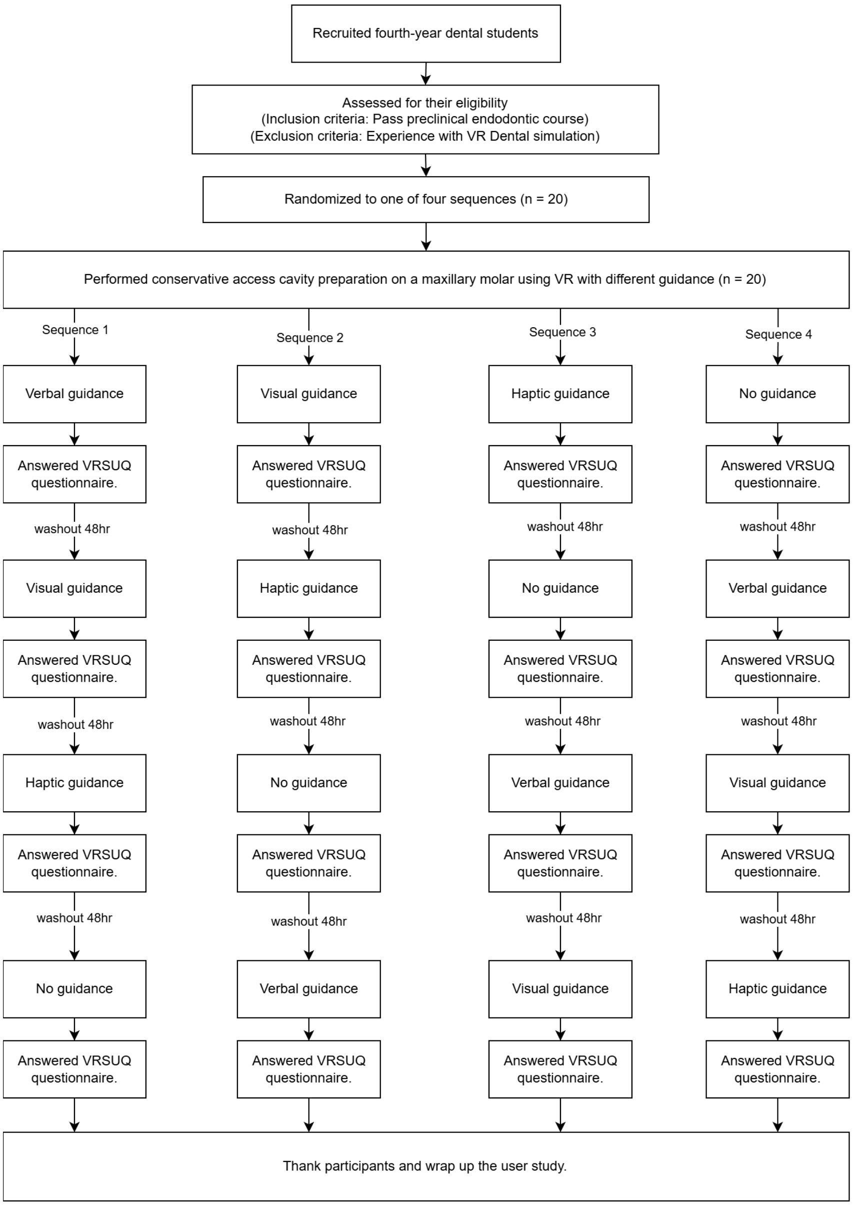

Figure 5.2: Flow diagram of the user study

5.4 DATA COLLECTION

This section describes the data that was collected after each session of the study to process further.

Two main methods were used for data collection in this study. The first method involved the automatic recording of performance data by the system after participants completed each task. These performance metrics were recorded by the simulator and included the following variables:

- **Guidance Method:**

  The mirror correction guidance modality provided to the participant during the session. This variable had four possible categories: visual guidance, verbal guidance, haptic guidance, and no guidance

- **Outcome Error Score:**

  A performance score used to evaluate the participant's performance in the minimally invasive endodontic access cavity preparation task. This metric was previously implemented in an earlier version of the dental simulator [16]. The score ranges from 0 to 15.

- **Task completion time (sec):**

  This value measured the total time required to complete the task, starting from the beginning of the operation until the system was closed.

- **Total duration during which the tooth was visible to the user while the bur was touching the tooth (sec):**

  This metric measured the total time during which the user could see the tooth in the mirror while the drill bur was in contact with the tooth.

- **Number of times the mirror was incorrectly oriented while the drill bur was touching the tooth (n):**

  This value increased whenever the mirror transitioned from a correct orientation (i.e., the tooth location was visible in the mirror) to an incorrect orientation (i.e., the tooth location was not reflected in the mirror due to the orientation) while the drill bur was in contact with the tooth.

- **Total duration of incorrect mirror orientation while the drill bur was touching the tooth (sec):**

  This metric measured the total time during which the mirror was incorrectly oriented, such that the tooth location was not visible to the user, while the drill bur was in contact with the tooth.

- **Number of times the mirror was correctly oriented but the line of sight was blocked while the drill bur was touching the tooth (n):**

  This value increased when the mirror was changed from the good state (correct orientation with the tooth visible) to the bad state (correct orientation but the tooth was occluded by the drill bur).

- **Total duration the mirror was correctly oriented but the line of sight was blocked while the drill bur was touching the tooth (sec):**

  This metric measured the total time during which the mirror was correctly oriented but the user's view of the tooth was obstructed by the drill bur.

The second method of data collection involved questionnaires. After completing each session, participants were asked to complete the Virtual Reality Usability Questionnaire (VRSUQ) [18]. The full list of questionnaire items is provided in Appendix A.3.1.

6

RESULTS

The results of the user study include participant characteristics, task performance outcomes, mirror-handling outcomes, and participants' perceptions of the system.

A 4x4 Latin square crossover ANOVA was conducted to examine the effect of guidance conditions (verbal, visual, haptic, and no guidance) on task performance metrics, mirror-handling metrics, and user perception metrics.

6.1 PARTICIPANT CHARACTERISTICS

A total of 20 participants completed the study (15 female [75%], 5 male [25%]). The mean age was 23.2 years (SD = 1.85; range = 22-30 years). Seventeen participants (85%) reported myopia, while three reported normal vision (15%). All participants were right-handed. No participants withdrew from the study, and all completed the four guidance conditions according to their assigned Latin square sequence.

6.2 PERFORMANCE OUTCOMES

This section presents performance outcome metrics, including the outcome error score and the total task duration. These metrics correspond to Research Question *R2*.

No statistically significant guidance effects were observed for the following performance outcome variables, including outcome error score and total task duration.

6.2.1 *Outcome Error Score*

Figure 6.1 illustrates the distribution of outcome error scores across the four guidance conditions. Verbal guidance shows the lowest mean error (M = 2.31) and relatively low variability (SD = 0.82), indicating slightly better and more consistent performance compared to the other conditions. In contrast, the haptic guidance condition has the highest mean error (M = 2.60) and the largest variability (SD = 1.34), suggesting less consistent performance.

Although some differences in the distributions can be visually observed, the violin plots show substantial overlap between conditions. A 4x4 Latin square crossover ANOVA indicated that the effect of guidance on outcome error score was not statistically significant, F(3, 54) = 0.305, p = 0.821. This suggests that the observed differences between

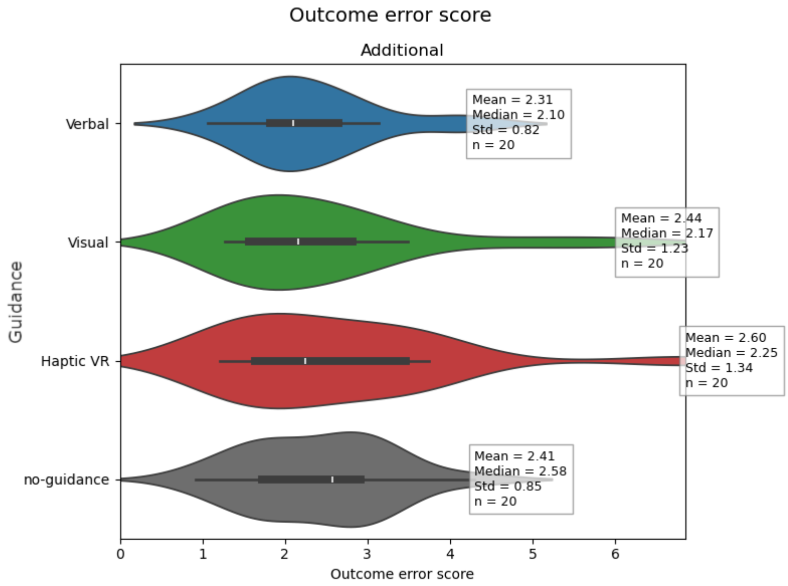

Figure 6.1: Outcome error score

guidance methods may be due to random variation rather than a true learning effect.

6.2.2 *Total Task Duration*

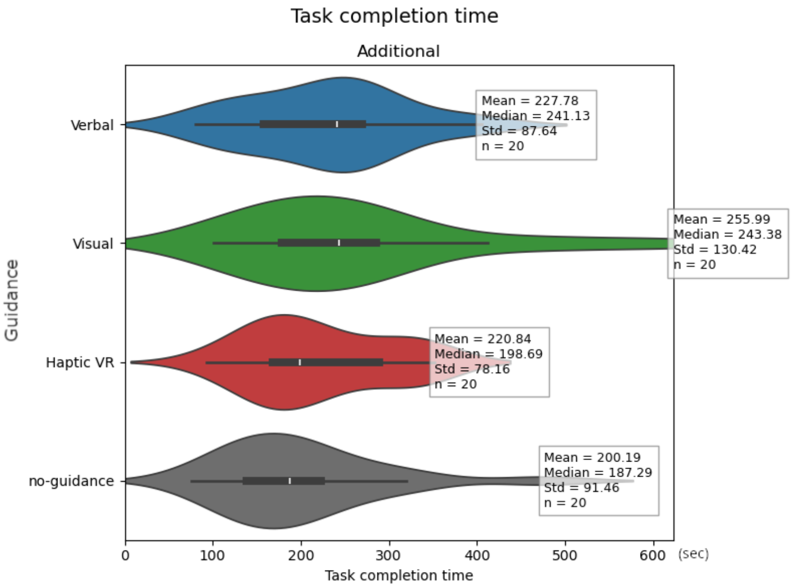

Figure 6.2: Task completion time

Figure 6.2 presents the distribution of task completion times across the four guidance conditions. The no-guidance condition shows the lowest mean completion time (M = 200.19 s), while the visual guidance condition exhibits the highest mean time (M = 255.99 s) and the largest variability (SD = 130.42). The haptic guidance condition shows slightly lower variability (SD = 78.16) compared to the other guidance methods, indicating relatively more consistent performance.

Despite these observed differences, the distributions across conditions show substantial overlap. A 4x4 Latin square crossover ANOVA revealed that the effect of guidance on task completion time was not statistically significant, F(3, 54) = 1.170, p = 0.330. This indicates that the observed differences in completion time between guidance conditions were not statistically meaningful.

6.3 MIRROR HANDLING OUTCOMES

This section presents mirror-handling metrics, including tooth visibility duration, mirror orientation error count, mirror orientation error duration, tooth occlusion count, and tooth occlusion duration. These metrics correspond to Research Question *R1*.

Based on the data collected in the previous chapter, filtering conditions were applied to three metrics to reduce noise and jitter in edge cases. These metrics included: mirror orientation errors count and tooth occlusions count. The following filtering conditions were applied:

- at least 1.0s (90 frames) elapsed between consecutive increment for each metric
- the state persisted for a minimum duration of 0.1s (9 frames) before an incrementation was recorded

A statistically significant guidance effect was observed for mirror orientation errors count during bur-tooth contact. No statistically significant guidance effects were observed for the remaining dependent variables.

6.3.1 *Tooth Visibility Duration*

Figure 6.3 illustrates the normalized tooth visibility duration relative to the total time during which the bur contacted the tooth across the four guidance conditions. Verbal guidance shows the highest mean visibility duration (M = 0.66), followed closely by visual guidance (M = 0.64). In contrast, the haptic guidance condition exhibits the lowest mean value (M = 0.57).

The visual guidance condition shows the smallest variability (SD = 0.16), indicating more consistent performance compared to the other conditions. The haptic guidance condition presents the largest variability (SD = 0.22), suggesting less consistent results across participants. Despite these differences, the distributions across conditions exhibit considerable overlap.

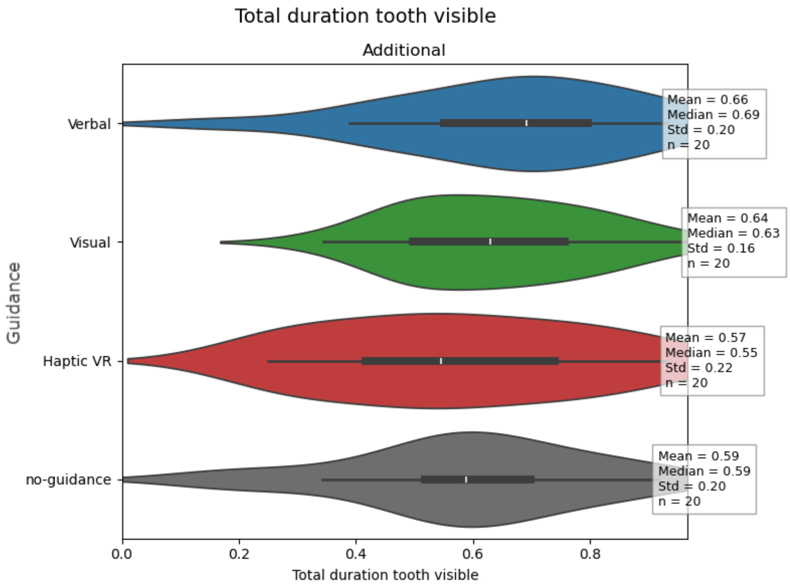

Figure 6.3: Normalized duration for which the tooth was visible while the bur was contacting the tooth

A 4x4 Latin square crossover ANOVA revealed that the effect of guidance on the normalized tooth visibility duration was not statistically significant, F(3, 54) = 1.542, p = 0.214.

6.3.2 *Mirror Orientation Errors*

6.3.2.1 *Mirror Orientation Errors Count*

Figure 6.4 illustrates the number of times the mirror was incorrectly oriented while the bur contacted the tooth across the four guidance conditions. The visual guidance condition exhibits the highest mean (M = 13.40) and median (Mdn = 14.50) error counts, suggesting that participants made mirror orientation errors more frequently under this guidance modality. In contrast, the no-guidance condition shows the lowest mean error count (M = 6.10), followed closely by the verbal guidance condition (M = 7.05).

The haptic guidance condition demonstrates the largest variability (SD = 8.60), indicating greater inconsistency in participant performance.

A 4x4 Latin square crossover ANOVA revealed a statistically significant guidance effect on the number of mirror orientation errors, F(3, 54) = 6.505, p = .001, indicating that the guidance modality significantly influenced the frequency of mirror orientation mistakes during the task.

Post hoc Dunnett comparisons demonstrated that:

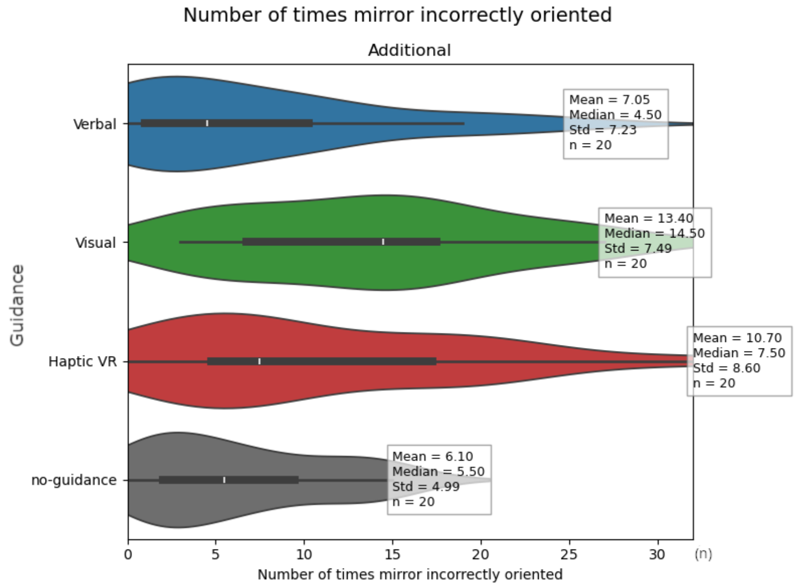

Figure 6.4: Number of times that the mirror was incorrectly oriented

- Visual guidance (M = 13.4) resulted in significantly more incorrect mirror orientations compared with the reference condition (p = .001).
- Haptic guidance (M = 10.7) also resulted in significantly more incorrect mirror orientations (p = .024).
- No significant difference was observed between verbal guidance (M = 7.05) and no guidance (M = 6.10; p = .537).

6.3.2.2 *Mirror Orientation Errors Duration*

Figure 6.5 illustrates the normalized duration of incorrect mirror orientation relative to the total time during which the bur contacted the tooth. Verbal guidance shows the lowest mean misalignment duration (M = 0.03), indicating fewer mirror orientation errors compared to the other conditions. In contrast, the visual guidance condition exhibits the highest mean value (M = 0.06).

The no-guidance condition shows the largest variability (SD = 0.07) and a pronounced right-tailed distribution, suggesting that while most participants maintained relatively short misalignment durations, a small number exhibited substantially longer errors. The haptic guidance condition shows moderate variability (SD = 0.05).

Despite these differences, substantial overlap exists between the distributions. A 4x4 Latin square crossover ANOVA revealed that the effect of guidance methods on mirror misalignment duration was not statistically significant, F(3, 54) = 1.737, p = 0.170.

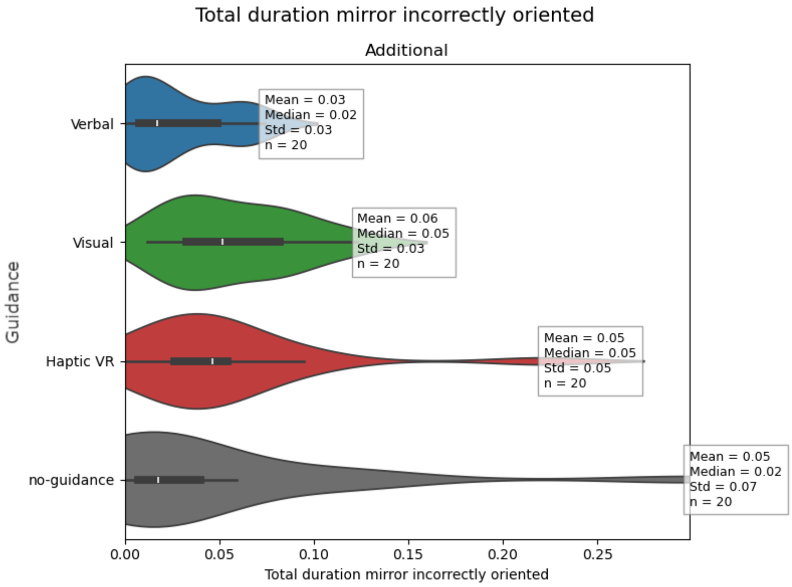

Figure 6.5: Normalized duration that the mirror was incorrectly oriented

6.3.3 *Tooth Occlusion*

6.3.3.1 *Tooth Occlusion Count*

Figure 6.6 presents the distribution of the number of times the tooth was obstructed in the mirror while the mirror itself was correctly oriented. The visual guidance condition shows the highest mean (M = 42.80) and median (Mdn = 39.00) values, as well as the largest variability (SD = 28.92), indicating that participants experienced more frequent visual obstructions under this condition.

In contrast, the verbal guidance (M = 29.90), haptic guidance (M = 31.65), and no-guidance (M = 28.00) conditions exhibit relatively similar distributions and lower obstruction frequencies. Among these, the haptic guidance condition shows slightly higher values compared to the verbal and no-guidance conditions.

A 4x4 Latin square crossover ANOVA revealed that the effect of guidance methods on the number of tooth visibility obstructions was not statistically significant, F(3, 54) = 1.874, p = 0.145, suggesting that the observed differences between conditions may be due to random variation.

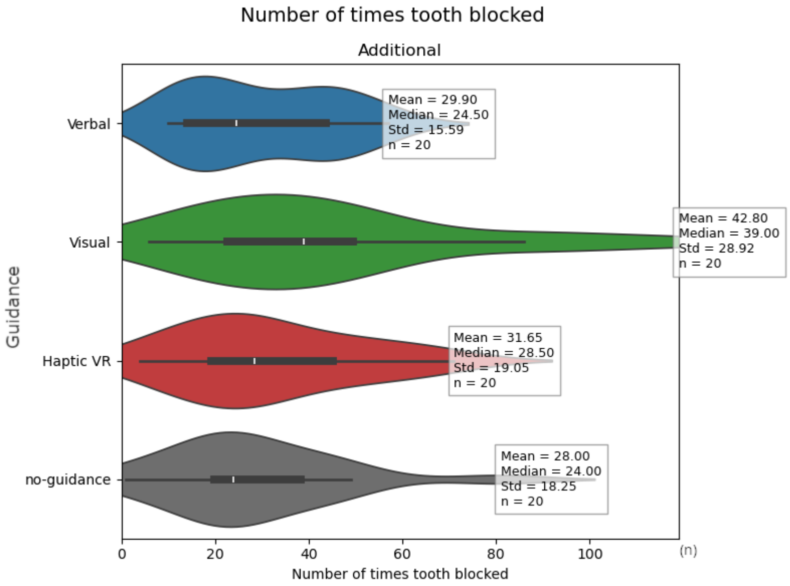

Figure 6.6: Number of times that the line of sight of the tooth inside the mirror was blocked

6.3.3.2 *Tooth Occlusion Duration*

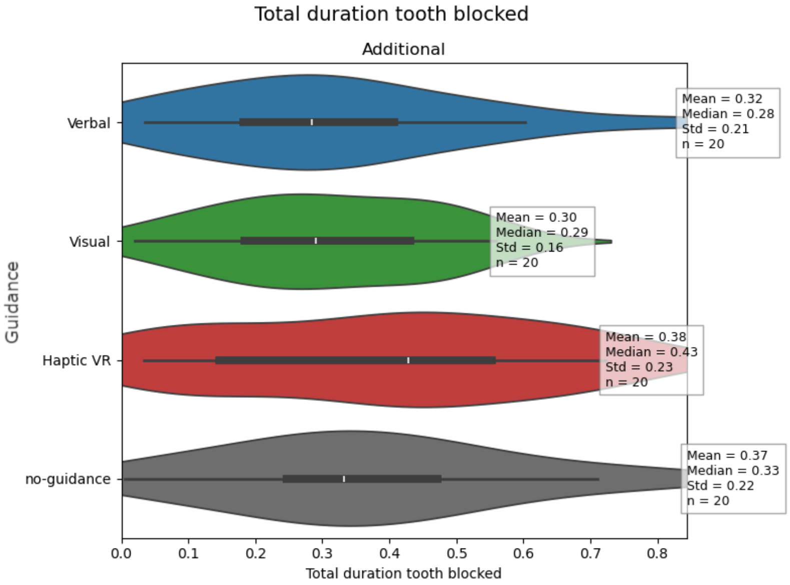

Figure 6.7: Normalized duration that the line of sight of the tooth inside the mirror was blocked

Figure 6.7 presents the distribution of the total duration during which the tooth was visually blocked by the bur head, normalized by the total drill-tooth contact time. The visual guidance condition shows the lowest mean obstruction duration (M = 0.30) and the smallest variability (SD = 0.16), suggesting slightly better visibility performance compared to the other conditions.

In contrast, the haptic guidance condition exhibits the highest mean (M = 0.38) and median (Mdn = 0.43) obstruction durations, indicating relatively longer periods during which the tooth was occluded by the tool. The verbal guidance (M = 0.32) and no-guidance (M = 0.37) conditions display similar distributions and intermediate values.

A 4x4 Latin square crossover ANOVA revealed that the effect of guidance methods on the normalized tooth obstruction duration was not statistically significant, F(3, 54) = 1.211, p = 0.315, suggesting that the observed differences between conditions may be attributable to random variation.

6.4 QUESTIONNAIRE RESULT

This section presents participants' perceptions metrics, including the quantitative usability outcomes score and the qualitative participants' feedback. These metrics correspond to Research Question *R*3.

6.4.1 *Usability Outcomes*

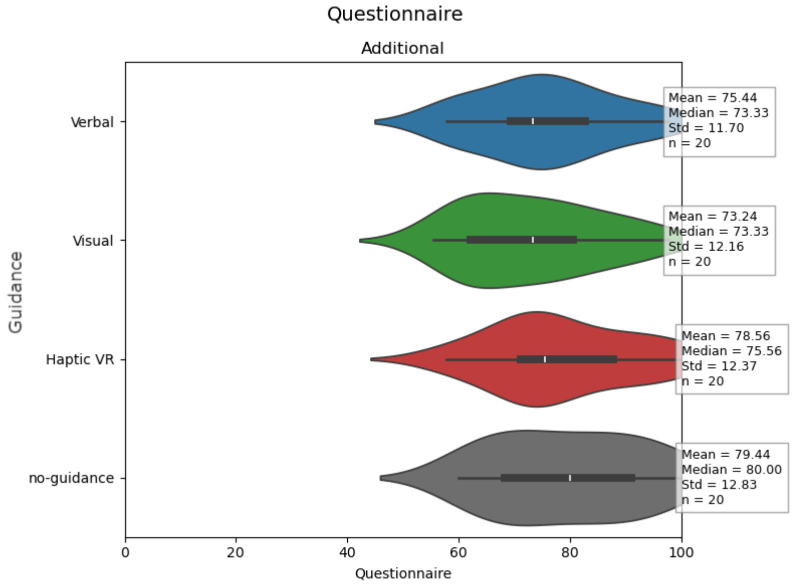

Figure 6.8: System usability questionnaire score

Figure 6.8 illustrates the distribution of Virtual Reality System Usability Questionnaire (VRSUQ) scores across the four guidance conditions. The no-guidance condition shows the highest mean usability score (M = 79.44), followed by the haptic guidance condition (M = 78.56). The verbal (M = 75.44) and visual (M = 73.24) guidance conditions exhibit slightly lower mean usability scores.

Despite these descriptive differences, the distributions across conditions show considerable overlap and similar variability. A 4x4 Latin square crossover ANOVA indicated that the effect of guidance condition on perceived system usability was not statistically significant, F(3, 54) = 2.431, p = 0.075.

6.4.2 *Participants' Perception*

In addition to the VRSUQ scores, participants provided qualitative feedback on the system and each guidance condition. Overall, the perception of the system was positive. Participants generally considered the system easy to use and helpful. However, several comments were related to the head-mounted display (HMD). Some participants reported that the headset was heavy and uncomfortable to wear, particularly when wearing glasses. Based on this feedback, future implementations may consider using a smaller and lighter headset with more easily adjustable lenses.

Regarding the guidance system, several participants noted that the guidance sometimes remained active even when they were already able to see the tooth. This situation could occur when the tooth was visible only at the edge of the mirror due to reflection. In such cases, the system suggested adjusting the mirror so that the tooth would be positioned closer to the center of the mirror, allowing a clearer view.

Participants' perception of the visual guidance condition was generally positive and it was considered helpful. However, several participants commented that the ghost mirror occasionally obstructed their view. These obstruction issues were related to the mirror-handling problems mentioned previously. Additionally, some participants suggested that combining visual and verbal guidance might be more helpful than using either guidance modality independently.

The perception of the verbal guidance was also highly positive, particularly for assisting mirror adjustments. Some participants suggested that the guidance should provide more explicit instructions on how to adjust the mirror. However, as discussed in the previous chapter, adding more directional guidance increases complexity and cognitive load. Longer instructions were also found to be less effective for mirror adjustment tasks performed in a confined environment. Another issue reported by participants was the same problem described earlier, where guidance was provided even when the tooth was already visible.

In contrast, the general perception of the haptic guidance was mostly negative. Many participants reported that the guidance forcefully pulled their hand toward locations they did not intend to move to. Additionally, some participants reported that the guidance was applied while they were drilling, which led to additional errors during task performance. Some participants also noted that the location suggested by the guidance was technically correct for viewing the tooth, but the root canals were not visible from that position. Overall, participants perceived the haptic guidance as obstructive. Because it directly applied force to the user's hand, it was considered more likely to cause errors during the task.

6.5 PERIOD AND SEQUENCE EFFECTS

No statistically significant period or sequence effects were observed (all $p > .05$). This indicates that the order of condition presentation did not significantly affect performance outcomes and suggests minimal carryover or learning effects across sessions.

7

DISCUSSION

This chapter discusses the effectiveness of the different guidance methodologies in the virtual reality dental training system. The results from the previous chapter are interpreted with respect to the research questions. The findings are compared across the four experimental conditions: visual guidance, verbal guidance, haptic guidance, and no guidance. In addition to the research questions, this chapter also discusses strengths of the study, and limitations and future works.

7.1 MIRROR HANDLING PERFORMANCE

Mirror handling performance was evaluated using several metrics, including tooth visibility duration, mirror orientation error count, mirror orientation error duration, tooth blocked count, and tooth blocked duration.

Overall, the results indicate that the effectiveness of the guidance methodologies for mirror handling were limited and inconsistent across the different metrics. Among the measured variables, only the mirror orientation error count showed a statistically significant difference between conditions. The analysis revealed that the visual guidance and haptic guidance conditions resulted in higher numbers of mirror orientation errors, while verbal guidance and the no-guidance condition showed lower error counts. This suggests that visual overlays or haptic force feedback may have interfered with participants' natural mirror adjustment strategies.

One possible explanation is that visual guidance introduced additional visual elements into the scene, such as the ghost mirror, which may have obstructed the participant's view during mirror manipulation. This interpretation is supported by the qualitative feedback from participants, who reported that the ghost mirror occasionally obstructed their line of sight. As a result, participants may focus more on the visual cues than on the mirror, which may divert their attention from the mirror orientation, leading to increased error counts.

Similarly, haptic guidance produced mixed outcomes in mirror handling. Although the haptic guidance was designed to assist users by guiding their hands toward the correct mirror orientation, several participants reported that the system occasionally pulled their hands toward unintended positions. In some cases, the suggested position allowed the tip of the tooth to be visible but did not provide a clear view of the root canals, which are critical for the dental procedure. This mismatch between the system's suggested position and the participants' intended working position may explain the increased variability and higher error counts observed in the haptic condition. This behavior could be caused by the algorithm prioritizing the tip of the tooth as the target location to be visible while not taking the root canals into account.

In contrast, verbal guidance demonstrated relatively stable performance across most mirror-handling metrics. While the differences were not statistically significant for most variables, the distributions generally indicated lower variability and fewer extreme errors compared to visual and haptic guidance. Participants also reported that verbal instructions were particularly helpful when adjusting the mirror. This suggests that verbal guidance may support mirror handling without interfering with the user's visual perception or motor control.

Interestingly, the no-guidance condition also showed competitive performance across several mirror handling metrics. In some cases, the descriptive statistics indicated slightly better performance than certain guidance conditions. This may suggest that participants were able to rely on their natural visuomotor coordination and adapt their mirror-handling strategies without external guidance. However, it should be noted that the variability in this condition was often higher, indicating that performance may depend strongly on individual skill levels.

Overall, these results suggest that verbal guidance may provide the most balanced support for mirror handling, while visual and haptic guidance may introduce additional challenges depending on their implementation.

7.2 TASK EXECUTION PERFORMANCE

Task execution performance was evaluated using two primary metrics: outcome error score and task completion time. These metrics reflect the overall accuracy and efficiency of the participants when performing the simulated dental procedure.

The statistical analysis revealed no significant differences between the guidance conditions for either outcome error score or task completion time. This suggests that the introduction of guidance did not substantially improve or degrade the participants' overall task performance compared to performing the task without guidance.

Although the statistical tests did not show significant differences, some descriptive trends were observed. For example, the verbal guidance condition showed the lowest mean and variability in outcome error score, indicating slightly better and more consistent performance compared to the other conditions. In contrast, the haptic guidance condition exhibited higher mean and variability in outcome error score, suggesting worse and less consistent performance among participants.

For task completion time, the no-guidance condition showed the lowest average completion time, while the visual guidance condition exhibited the longest completion times and the largest variability. One possible explanation is that participants may have spent additional time interpreting the visual guidance cues before making adjustments to the mirror or the drilling tool. Similarly, participants receiving haptic or verbal guidance may have needed additional time to interpret and respond to the feedback provided by the system.

These findings suggest that while guidance mechanisms may provide assistance during specific subtasks, such as mirror manipulation, they may also introduce additional cognitive load. Participants may need to process and interpret the guidance information while simultaneously performing the motor task, which could offset potential efficiency gains.

Overall, the results indicate that none of the guidance methodologies produced a clear improvement in overall task performance compared to the no-guidance condition.

7.3 USER PERCEPTION OF THE SYSTEM

User perception of the system was evaluated using the Virtual Reality System Usability Questionnaire (VRSUQ) as well as qualitative participant feedback.

The quantitative analysis of the VRSUQ scores showed no statistically significant differences in perceived usability between the guidance conditions. However, the descriptive statistics indicated that the no-guidance condition received the highest average usability score, while the visual guidance condition received the lowest score among the four conditions.

One possible interpretation is that introducing guidance mechanisms may increase the perceived complexity of the system, particularly if the guidance cues are not fully aligned with the user's expectations or workflow. Participants may need additional time to understand how to interpret and respond to the guidance, which can affect their perception of system usability.

The qualitative feedback provided further insights into the participants' experiences with the system. Overall, participants reported that the system was generally easy to use and helpful for training purposes. However, several hardware-related issues were mentioned, particularly regarding the head-mounted display, which some participants found heavy and uncomfortable to wear, especially when wearing glasses.

Participants' opinions of the individual guidance conditions also varied. Visual guidance was generally perceived as helpful, although some participants reported that the ghost mirror occasionally obstructed their view. Verbal guidance received the most consistently positive feedback, particularly for assisting mirror adjustments. Some participants suggested that more explicit directional instructions could further improve the effectiveness of the verbal guidance.

In contrast, haptic guidance received mostly negative feedback. Participants reported that the system sometimes applied forces that pulled their hand toward unintended positions or interfered with their drilling movements. Because haptic feedback directly influences the user's motor control, these issues were perceived as more disruptive than the visual or verbal guidance methods.

7.4 STRENGTHS OF THE STUDY

This study used a balanced 4x4 Latin square crossover design to reduce potential order and carryover effects. Each participant completed all conditions, enabling within-subject comparisons that minimized inter-individual variability and improved statistical sensitivity. The lack of significant period or sequence effects indicates that the crossover structure and washout interval were appropriate.

7.5 LIMITATIONS AND FUTURE WORK

Several limitations should be considered. First, the sample size for each condition was relatively small ($n = 20$), which may limit the statistical power to detect subtle differences between guidance modalities. In addition, the study evaluated performance in a simulated VR environment, which may not fully replicate clinical conditions. Lastly, the study also evaluated a single simulated dental task within a limited training session. Longer-term training studies may reveal different effects as participants adapt to feedback modalities over time.

Future research should investigate the effects of guidance modalities across longer training sessions or multiple practice trials, where the benefits of feedback systems may become more pronounced as users refine their procedural skills. Combining different guidance modalities may also provide further insight into how VR training environments can best support skill development. Examining the interaction between learner expertise and feedback modality could reveal how different guidance methods vary in effectiveness depending on user skill level. Exploring new types of guidance feedback may help assess the effectiveness of alternative methodologies. Finally, the intensity and timing of feedback should be further investigated to determine which approaches yield the greatest learning gains.

7.6 SUMMARY OF FINDINGS

Overall, the results suggest that the effectiveness of the guidance methodologies varied depending on the evaluation criteria.

For mirror handling, verbal guidance appeared to provide the most stable performance, while visual and haptic guidance sometimes introduced additional challenges. For task execution performance, none of the guidance conditions produced significant improvements compared to the no-guidance condition. Finally, regarding user perception, verbal guidance was generally perceived positively, visual guidance received mixed feedback, and haptic guidance was often perceived as intrusive or disruptive.

These findings emphasize the need for careful design of feedback systems in immersive training environments. Although multimodal feedback is commonly expected to improve learning, overly complex or poorly integrated guidance may impose additional cognitive load that disrupts fine motor skill performance.

For VR-based dental training systems, designers should consider the cognitive demands imposed by multimodal feedback and evaluate whether such modalities meaningfully enhance skill acquisition or inadvertently increase cognitive load. In some contexts, simpler guidance approaches—such as verbal instruction or minimal feedback—may provide comparable performance outcomes without increasing cognitive load.

8

CONCLUSION

This study investigated the effectiveness of three guidance modalities-visual, verbal, and haptic-on mirror handling performance, task execution, and user perception in a VR-based dental simulator for minimally invasive endodontic access cavity preparation. A randomized 4x4 Latin square crossover design was employed with 20 fourth-year dental students, enabling within-subject comparisons across all four conditions including a no-guidance baseline.

The findings yielded one statistically significant result: guidance modality significantly affected the numbers of mirror orientation errors. Contrary to initial hypotheses, visual and haptic guidance produced significantly more mirror orientation errors than the no-guidance condition, while verbal guidance performed comparably to no guidance. This suggests that more complex guidance modalities may disrupt rather than support natural mirror adjustment strategies, particularly when visual overlays obstruct the operative field or haptic forces direct the hand toward unintended positions.

For task execution metrics-including outcome error score and task completion time-no statistically significant differences were found between conditions. Descriptively, verbal guidance showed the lowest mean error score, while the no-guidance condition produced the shortest completion times, suggesting that guidance mechanisms may impose cognitive overhead that partially offsets their instructional benefit.

User perception results, assessed through the Virtual Reality System Usability Questionnaire, also showed no statistically significant differences between conditions. However, qualitative feedback revealed a consistent pattern: verbal guidance was perceived most positively, visual guidance received mixed responses due to occasional obstruction by the ghost mirror, and haptic guidance was broadly perceived as intrusive and disruptive to motor control.

Taken together, these results reject all hypotheses. We anticipated that developed guidance methodology would outperform the no-guidance condition in terms of mirror handling performance, task execution performance, and user perception. The quantitative results show that the no-guidance condition performs comparatively similarly, if not better, than the visual and haptic guidance conditions in most metrics, while performing the most similarly to verbal guidance. This is clearly visibility for H3, which no-guidance performed better than all other guidance conditions from the system usability questionnaire result.

These findings carry important implications for the design of VR-based dental training systems. Multimodal feedback should not be assumed to be inherently beneficial; guidance that is poorly calibrated or cognitively demanding may impair performance rather than enhance it. Simpler, non-intrusive feedback mechanisms such as concise verbal cues may offer comparable or superior outcomes relative to more complex modalities for tasks requiring fine motor control under indirect vision.

Future work should investigate longer training protocols to capture skill development over time, explore the new guidance methodologies and the combination of them, and examine how individual differences in spatial ability and prior clinical experience interact with guidance modality effectiveness. Combining verbal guidance with minimal visual cues, as suggested by participants, may represent a particularly promising direction for future system design.

A

APPENDIX

A.1 FIGURES

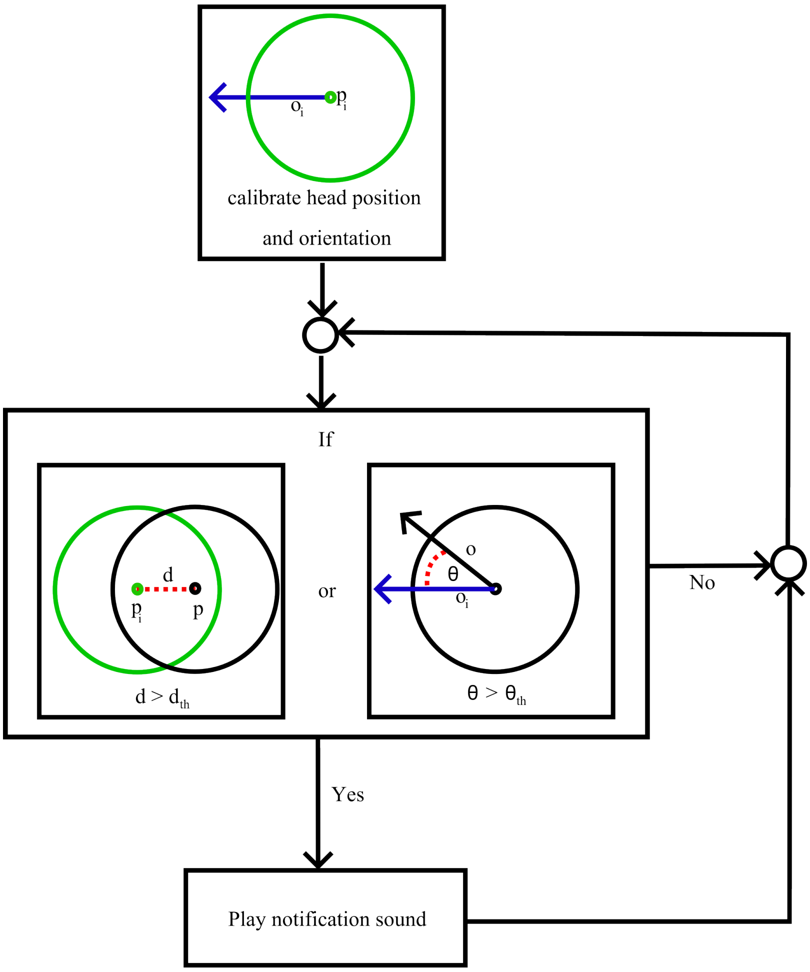

Figure A.1: The diagram illustration of posture correction logic

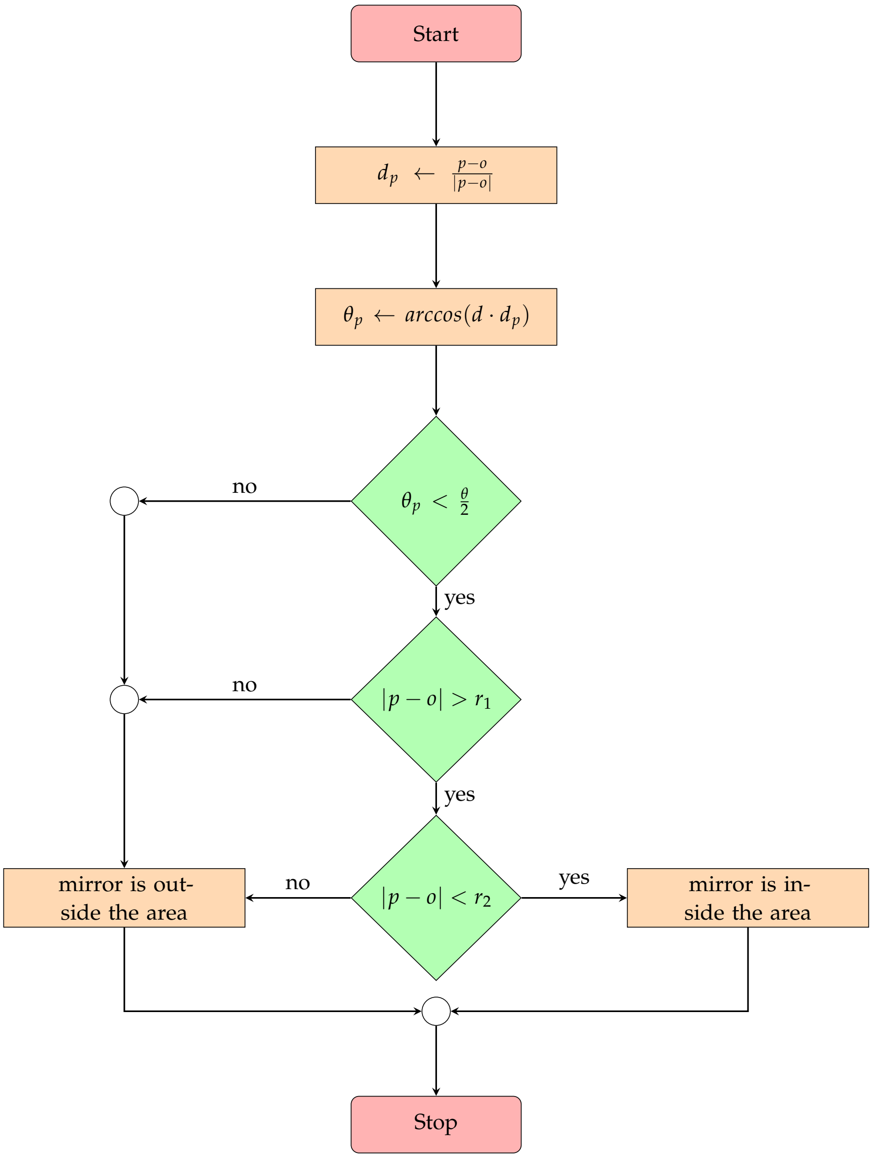

Figure A.2: The diagram illustration of check if mirror is inside the optimal area

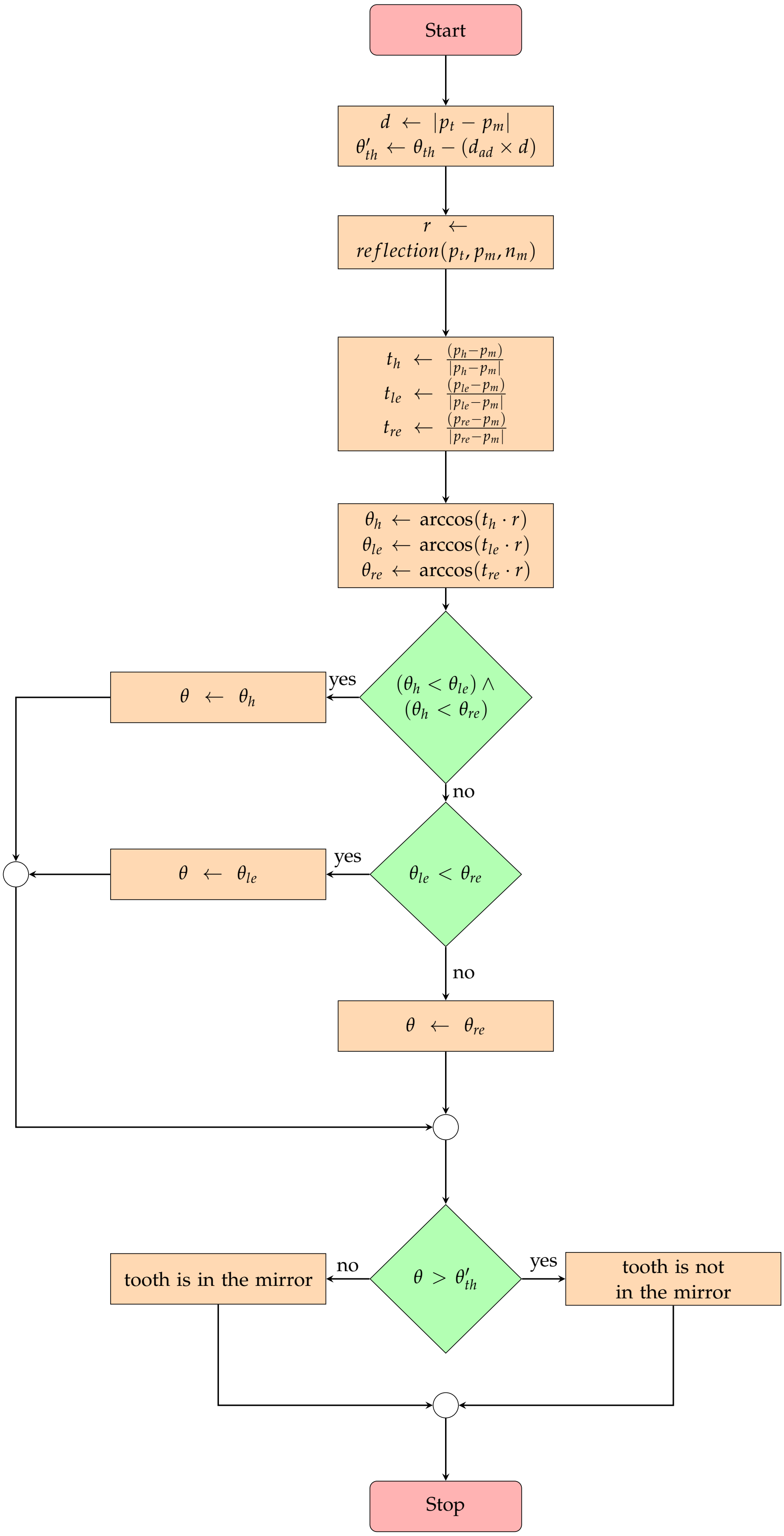

Figure A.3: the diagram for determining if the tooth is in the mirror

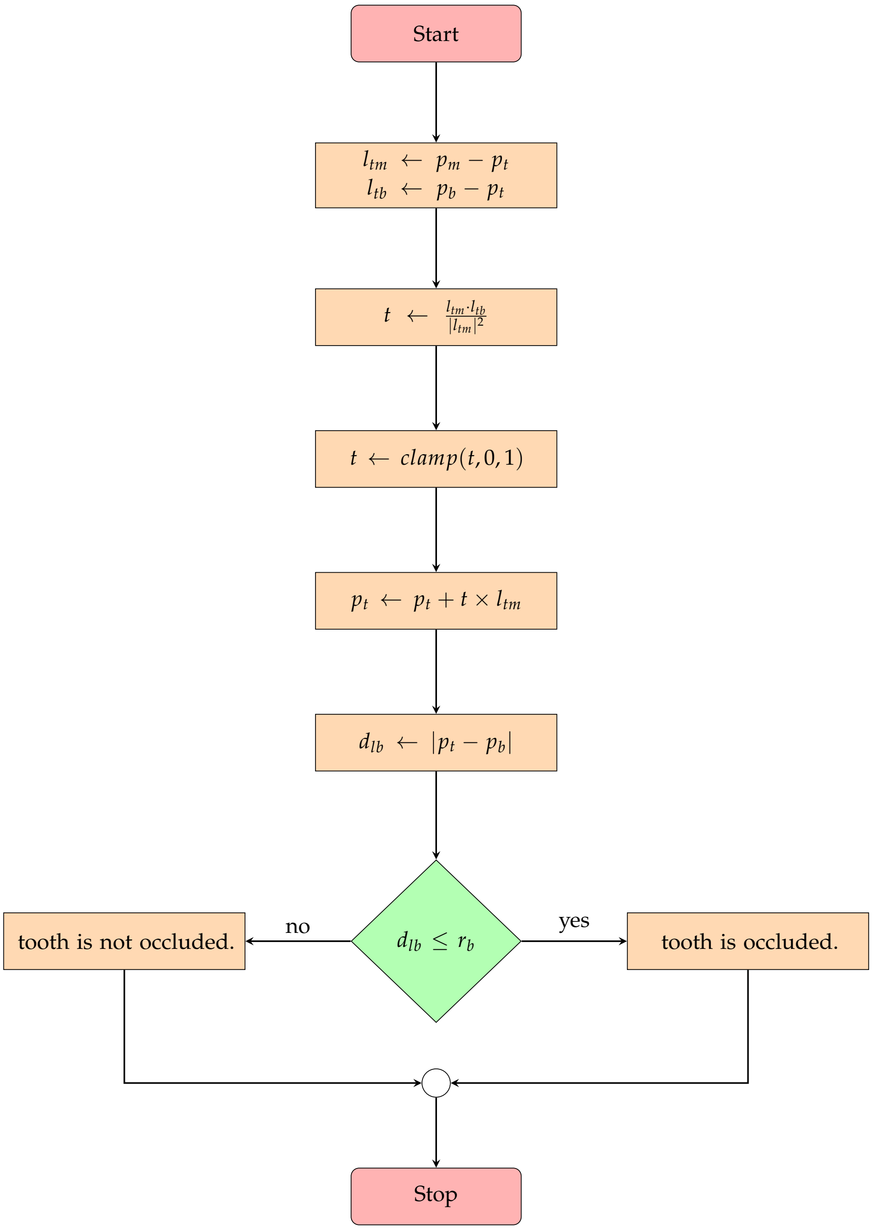

Figure A.4: The diagram visualization of how to determine if the mirror is occluded.

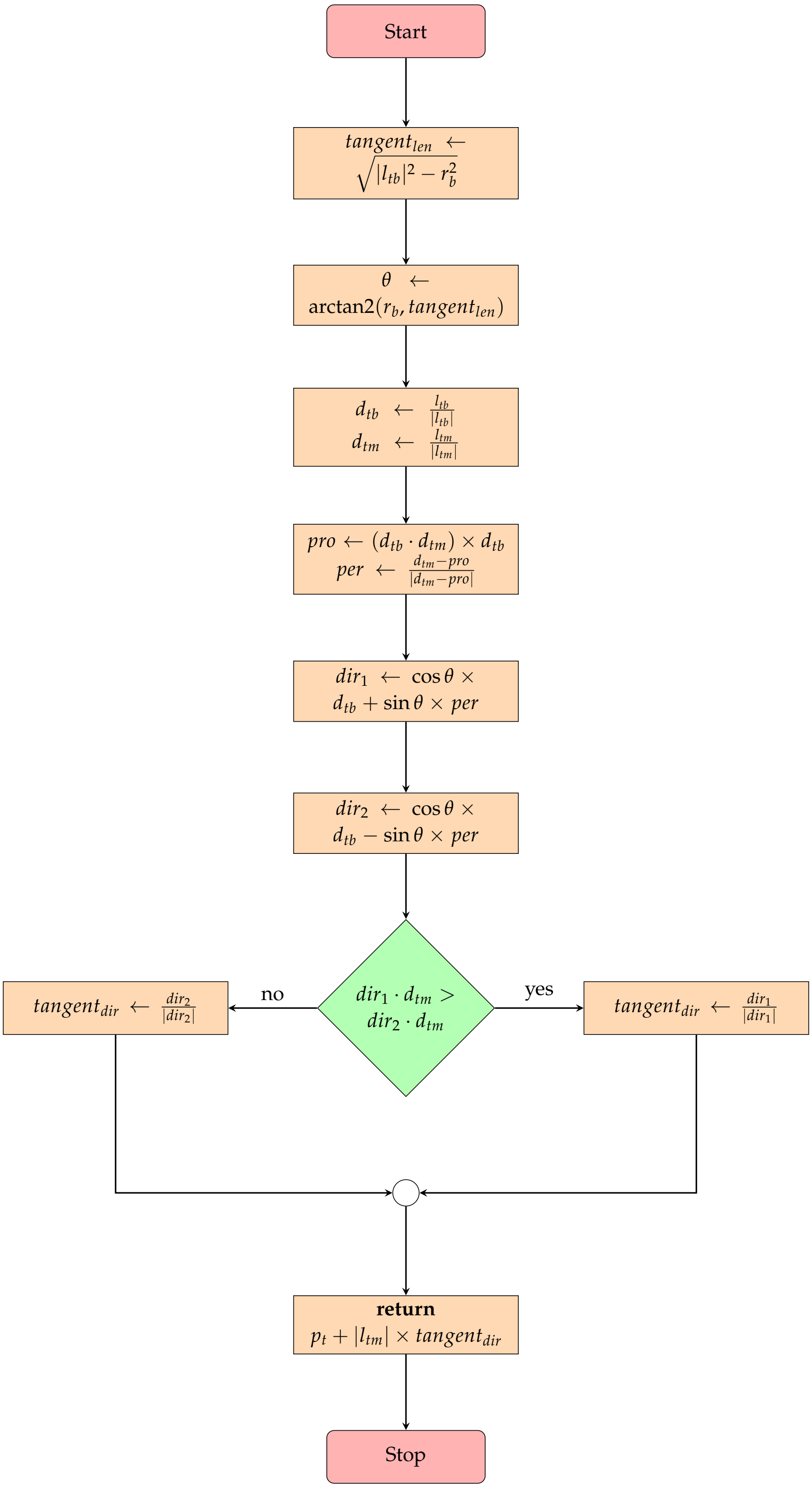

Figure A.5: The diagram visualization of the calculation of mirror position if occluded

A.2 ALGORITHMS

A.2.1 *Optimal Area*

Algorithm 8 Check Whether the Mirror is Inside the Optimal Area

```
$o \leftarrow$ cone origin
$d \leftarrow$ cone direction
$\theta \leftarrow$ cone angle
$r_1 \leftarrow$ area inner radius
$r_2 \leftarrow$ area outer radius
$p \leftarrow$ mirror position
$d_p \leftarrow \frac{p-o}{|p-o|}$
$\theta_p \leftarrow arccos(d \cdot d_p)$
if $(\theta_p < \frac{\theta}{2}) \wedge (|p-o| > r_1) \wedge (|p-o| < r_2)$ then
    return True;
else
    return False;
end if
```

A.2.2 *Calculate Reflection Vector*

Algorithm 9 Reflection

```
$s \leftarrow$ source location
$t \leftarrow$ reflection location
$n \leftarrow$ reflection normal
$i \leftarrow \frac{t-s}{|t-s|}$
$r \leftarrow \frac{i-(2\times(i \cdot n)\times n)}{|i-(2\times(i \cdot n)\times n)|}$
return $r$
```

A.2.3 *Check if mirror is occluded*

Algorithm 10 Is View Occluded

```
$l_{tm} \leftarrow p_m - p_t$
$l_{tb} \leftarrow p_b - p_t$
$t \leftarrow \frac{l_{tm} \cdot l_{tb}}{|l_{tm}|^2}, t \in [0, 1]$
$d_{lb} \leftarrow |(p_t + t \times l_{tm}) - p_b|$
if $d_{lb} \leq r_b$ then
    return True
end if
```

A.2.4 *Calculate the New Mirror when the Mirror is Occluded*

Algorithm 11 Find New Location of the Line of Sight Occluded

```
$tangent_{len} \leftarrow \sqrt{|l_{tb}|^2 - r_b^2}$
$\theta \leftarrow \text{arctan2}(r_b, tangent_{len})$
$d_{tb} \leftarrow \frac{l_{tb}}{|l_{tb}|}$
$d_{tm} \leftarrow \frac{l_{tm}}{|l_{tm}|}$
$pro \leftarrow (d_{tb} \cdot d_{tm}) \times d_{tb}$
$per \leftarrow \frac{d_{tm} - pro}{|d_{tm} - pro|}$
$dir_1 \leftarrow \cos\theta \times d_{tb} + \sin\theta \times per$
$dir_2 \leftarrow \cos\theta \times d_{tb} - \sin\theta \times per$
$tangent_{dir} \leftarrow \frac{dir_1}{|dir_1|}$
if $dir_1 \cdot d_{tm} < dir_2 \cdot d_{tm}$ then
    $tangent_{dir} \leftarrow \frac{dir_2}{|dir_2|}$
end if
return $p_t + |l_{tm}| \times tangent_{dir}$
```

A.2.5 *Ghost Mirror Orientation*

Algorithm 12 Ghost Mirror Orientation

```
$p_t \leftarrow$ tooth position
$p_h \leftarrow$ head position
$p_m \leftarrow$ ghost mirror position
$n_m \leftarrow$ ghost mirror normal
$r_m \leftarrow$ ghost mirror rotation
$r \leftarrow refection(s : p_t, t : p_m, n : n_m)$
$t \leftarrow \frac{p_h - p_m}{|p_h - p_m|}$
$\theta_{xy} \leftarrow \text{arctan2}((t_x \times r_y) - (t_y \times r_x), (t_x \times r_x) + (t_y \times r_y))$
$\theta_{xz} \leftarrow \text{arctan2}((t_x \times r_z) - (t_z \times r_x), (t_x \times r_x) + (t_z \times r_z))$
$r_m \leftarrow r_m + rotation(pitch : \theta_{xz}, yaw : \theta_{xy}, roll : 0)$
return $r_m$
```

A.2.6 *Direct Haptic Position Calculation*

Algorithm 13 Direct Haptic Position Calculation

```
$p_t \leftarrow$ tooth position
$p_h \leftarrow$ head position
$p_m \leftarrow$ mirror position
$n_m \leftarrow$ mirror normal
$s \leftarrow$ step size
$D \leftarrow$ possible directions to move $p_m$
$r \leftarrow relfection(s : p_t, t : p_m, n : n_m)$
$t \leftarrow \frac{p_h - p_m}{|p_h - p_m|}$
$\theta \leftarrow \arccos(t \cdot r)$
$\theta_{min} \leftarrow \infty$
for $d_i \in D$ do
    $p_{mi} \leftarrow p_m + d_i \times s$
    $r_i \leftarrow relfection(s : p_t, t : p_{mi}, n : n_m)$
    $\theta_i \leftarrow \arccos(t \cdot r_i)$
    if $\theta_i < \theta_{min}$ then
        $p'_m \leftarrow p_{mi}$
        $\theta_{min} \leftarrow \theta_i$
    end if
end for
return $p'_m$
```

A.3 USER STUDY

A.3.1 *Virtual Reality System Usability Questionnaire (VRSUQ)*

1. The system responded well to my manipulations as expected with no delays.
2. I think the virtual reality system provides clear feedback on my manipulations.
3. I kept making errors/mistakes while using the virtual reality system.
4. I could clearly understand the information presented within the virtual environment.
5. I think this system is user-friendly, straightforward to learn, and designed in such a way that most people will find it easy to adapt to.
6. I think it is easy to correct errors made during virtual reality experiences.
7. I enjoyed the virtual reality experience.
8. I felt dizzy, motion sickness, or a headache while experiencing virtual reality.
9. While experiencing virtual reality, I felt mental burdens such as tension, frustration, and time pressure.

A.3.2 *VRSUQ Mean Scores*

Item	Description	Verbal Mean (SD)	Visual Mean (SD)	Haptic Mean (SD)	No guidance Mean (SD)
1	System responded well to user manipulations without delays	4.00 (0.65)	4.00 (0.68)	4.15 (0.53)	4.20 (0.70)
2	VR system provided clear feedback on manipulations	3.75 (0.70)	4.00 (0.65)	4.10 (0.42)	4.15 (0.71)
3(-)	I kept making errors while using the VR system	4.00 (0.62)	4.00 (0.57)	4.20 (0.70)	4.25 (0.78)
4	Information presented in the virtual environment was easy to understand	3.75 (0.58)	3.55 (0.64)	4.15 (0.51)	4.20 (0.69)
5	The system was user-friendly and easy to learn	4.00 (0.68)	3.6 (0.58)	4.10 (0.63)	4.15 (0.72)
6	It was easy to correct errors during VR use	4.00 (0.61)	4.00 (0.51)	4.20 (0.69)	4.25 (0.57)
7	I enjoyed the virtual reality experience	4.20 (0.74)	4.10 (0.65)	4.10 (0.52)	4.15 (0.71)
8(-)	I experienced dizziness or motion sickness during VR use	4.00 (0.62)	4.00 (0.59)	4.15 (0.51)	4.20 (0.58)
9(-)	I experienced mental burden such as tension or frustration during VR use	4.45 (0.53)	4.15 (0.57)	4.15 (0.51)	4.15 (0.59)
	Overall usability score (1 - 100)	75.44 (11.70)	73.24 (12.16)	78.56 (12.37)	79.44 (12.83)

Table A.1: Mean and standard derivation VRSUQ scores by guidance condition for each item

A.3.3 *Participants' Comments on the System*

A.3.3.1 *General Commnets*

- The headset is slightly too heavy, causing my head to tilt downward during use.
- The system is easy to use, and the visuals are comfortable for the eyes.
- I felt relaxed while working; it was enjoyable and made me want to practice again.
- Wearing contact lenses is better than wearing glasses while using the system.
- While drilling, it was difficult to clearly see the preparation boundaries. I had to stop drilling and check with the mirror.
- I am not accustomed to working without a foot switch.

A.3.3.2 *Commnets on the Verbal Guidance*

- Verbal guidance was very helpful; it felt like having someone guiding me continuously whenever the mirror was in the wrong position.
- The audio reminder that the bur was not visible was useful, as it prevented me from drilling while not being able to see the bur.
- Overall, the instructions helped me adjust the mirror position appropriately.
- The system should also provide guidance on how to adjust the mirror.
- Sometimes I felt that I could already see the bur, but the system still instructed me to adjust, so I was unsure how clearly the bur needed to be visible.
- The audio instructions were distracting at times. In some positions, I could already see clearly, but the system still prompted me to adjust.

A.3.3.3 *Commnets on the Visual Guidance*

- The visual symbols were difficult to interpret.
- The cone-shaped indicator effectively helped identify the correct mirror position.
- The green mirror indicator served as a good reminder.

- When I was unable to find the correct mirror angle, the system provided very helpful guidance.
- The green mirror indicator appeared too frequently. Often, even when the tooth was visible, the green mirror was displayed, preventing me from continuing drilling.
- The green mirror overlay was too opaque; it should be more transparent.
- An accompanying audio alert would be helpful.

A.3.3.4 *Commnets on the Haptic Guidance*

- The system applied resistance or pulled my hand back, which altered the position where I intended to drill.
- The system pulled the hand holding the mirror during drilling, leading to errors.
- The system helped adjust the mirror direction so that the tooth was visible, but the root canal orifice was not clearly visible.
- I felt resistance in my hand but did not understand in which direction I should move the mirror.
- I really liked the haptic guidance.

A.4 USE OF AI-BASED APPLICATIONS

	AI-based	Purpose	Aspect of the Work Affected	Prompt (Entry)	Comment
1	ChatGPT, Claude	Improve writing	Grammar and paragraphs wording	Check these paragraphs for grammar and improve them: "(the paragraph)"	The result provided the improved paragraphs with no grammar errors and easier to follow.
2	ChatGPT, Claude	Proof reading	Grammar, paragraphs wording, and thesis structure	Rate this thesis and tell me if it can be improved	It helped me s on several errors and improved some parts of the thesis.
3	ChatGPT	Help with results analysis	Result report	Given the plots, rate my analysis: "(the paragraph and the image)"	The result improved my analysis and pointed out some parts that were missed.
4	Claude	Assisting implementation	Implementation of tangent calculation	Given a sphere, point A, and point B in a 3D space, find the tangent line from point A on the sphere that is similar to the line from A to B.	The result provided me the initial starting code, which was then adjusted later.
5	Consensus	Find relevant literature	Literature research	Guidance methodologies for practicing psychomotor skills	Found several relevant research articles.

Table A.2: The list of AI used as mentioned in the Declaration of Authorship

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