

Investigating Adaptive Hand Visibilities for Accurate 3D User Interactions in Augmented Reality

Rumeysa Turkmen
Concordia University,
Montreal, Quebec, Canada *

Nour Hatira
Concordia University,
Montreal, Quebec, Canada †

Robert J Teather
Monash University,
Clayton, Victoria, Australia ‡

Marta Kersten-Oertel
Concordia University,
Montreal, Quebec, Canada §

Wolfgang Stuerzlinger
Simon Fraser University,
Vancouver, British Columbia, Canada ¶

Anil Ufuk Batmaz
Concordia University,
Montreal, Quebec, Canada ||

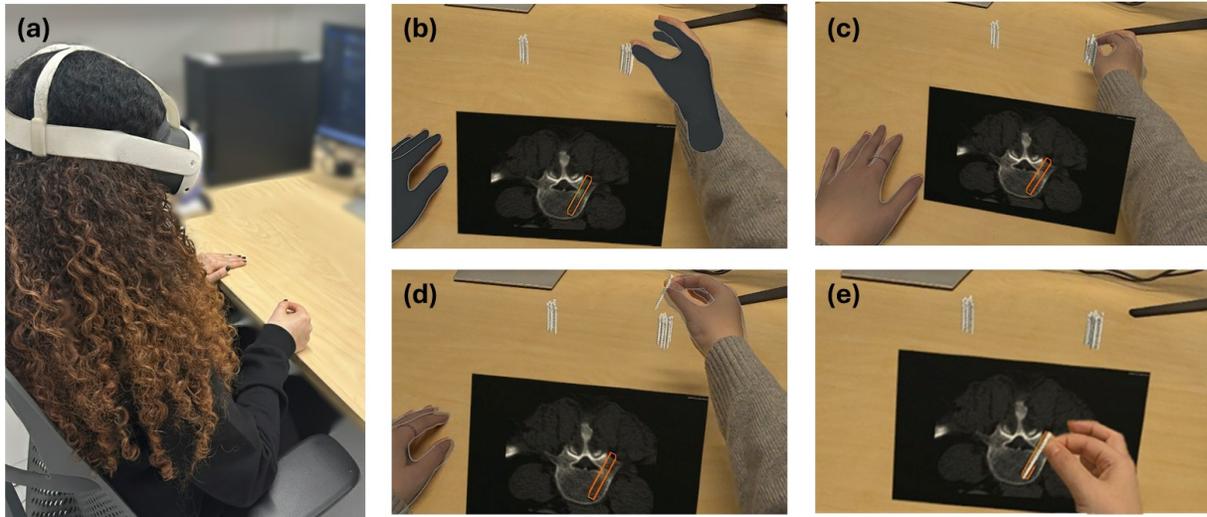


Figure 1: (a) A participant performing the AR Pedicle Screw Placement task. Adaptive hand visibility across different movement phases: (b) during the reaching phase, the virtual hand avatar is opaque while approaching the target; (c) during the grasping phase, the virtual hand avatar becomes transparent when picking up the screw; (d) during the transporting phase, the virtual hand avatar remains transparent while moving the screw toward the target area; and (e) during the inserting phase, the virtual hand avatar becomes invisible.

ABSTRACT

Augmented Reality (AR) tasks that require fine motor control often rely on visual hand representations, yet fully visible hands can introduce occlusion and reduce accuracy. In this work, we investigate adaptive hand visualization techniques that dynamically adjust hand visibility based on the current interaction sub-task to improve accuracy in AR. We designed an AR-based pedicle screw placement task, in which users insert virtual screws into a physical spine model. To evaluate how hand visualization affects task performance, we conducted a user study with 15 participants who performed the task under five hand visualization conditions: OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED visibility, and POSITION-BASED visibility. Our results show that adaptive visualization techniques significantly improve screw placement accu-

racy compared to the commonly used opaque hand representation. These findings demonstrate the benefits of dynamically adapting hand visibility can support accuracy-critical interactions.

Index Terms: Hand Visibility, Accuracy, Augmented Reality.

1 INTRODUCTION

Augmented Reality (AR) systems enable users to interact with digital content while maintaining visual access to the physical world [13]. Unlike Virtual Reality (VR), where the entire environment is virtual [20], AR interactions must carefully balance digital overlays with real-world visual cues to avoid occlusion, clutter, or misalignment between physical and virtual elements. In this context, the visualization of the user’s hands is important, as they often share the same visual space as task-relevant physical objects [4].

Recent advances in head-mounted displays (HMDs) have enabled hand tracking, allowing users to interact with virtual content using their own hands rather than handheld controllers. Hand interaction is more natural, intuitive, and supports direct manipulation [11, 10, 1]. As a result, a growing body of research has investigated how different hand representations, such as opaque and transparent hands, affect user experience and task performance in VR [7, 15, 19, 21].

However, hand visualization in AR poses different challenges. Although hand avatars provide useful feedback about hand pose and

*e-mail: rumeysa.turkmen@mail.concordia.ca

†e-mail: nour.hatira@mail.concordia.ca

‡e-mail: rob.teather@monash.edu

§e-mail: marta.kersten@concordia.ca

¶e-mail: w.s@sfu.ca

||e-mail: ufuk.batmaz@concordia.ca

motion, users can also see their real hands, resulting in multiple representations of the hands in the same visual space. This overlap can increase visual clutter, making the workspace feel crowded and obscuring task-relevant details particularly in fine motor tasks, where targets are small and accurate alignment is required. In such cases, opaque hand visualizations can occlude interaction targets, leading to misalignment and reduced accuracy [22, 9]. Consequently, hand visualization design plays a key role in supporting accurate interactions in AR.

Prior research has explored alternative hand visualizations. Studies in both VR and AR have examined transparent and invisible hand representations, showing that reducing hand visibility—by making the virtual hand partially transparent or invisible—can improve placement accuracy by minimizing visual clutter and avatar-induced occlusion in object manipulation tasks [22, 5, 24, 9]. However, manipulation tasks are often composed of multiple movement phases, such as reaching, grasping, transporting, and inserting objects [24]. Each movement phase places different visual and motor demands on the user. As a result, a hand visualization that is beneficial during reaching or grasping may become detrimental during the inserting phase by obscuring alignment cues or contact points.

Recent VR research demonstrated that the effectiveness of hand visualization depends strongly on the current movement being performed. Voisard et al. [24] found that opaque, transparent, and invisible hand representations yield different levels of placement accuracy across movement phases in a fine motor task. Building on these findings, subsequent work [21] introduced adaptive hand visualization techniques that dynamically adjust hand visibility based on movement speed or proximity to interaction-critical elements. These adaptive techniques were shown to improve placement accuracy during VR interactions.

Despite these promising results in VR, the impact of adaptive hand visibility techniques in AR has not been investigated yet. Unlike VR, AR introduces additional perceptual complexity due to the simultaneous presence of physical objects, virtual overlays, and real-world visual cues. As a result, findings from VR cannot be directly assumed to generalize to AR tasks.

To investigate this, we adapted a Pedicle Screw Placement (PSP) task from prior VR work. PSP is a surgical procedure in which users place screws into a spine. This task requires high spatial accuracy and fine motor control, which makes it an ideal task for evaluating hand visualization techniques [27]. PSP has been widely studied in both AR [29, 28, 14] and VR environments [27, 21], and can be systematically decomposed into movement phases such as reaching, grasping, transporting, and inserting [24, 23]. This structure allows for reproducible evaluation of user performance.

In this work, we design an AR-based PSP task incorporating five hand visualization techniques: OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED visibility, and POSITION-BASED visibility. The latter two techniques dynamically adapt hand visibility based on movement speed or proximity to the insertion target, respectively. We then conduct a controlled user study to examine whether adaptive hand visualization techniques improve accuracy and task performance compared to commonly used static hand representations.

2 RELATED WORK

2.1 Hand Visualization

To understand the effect of hand visualizations on user performance, prior work has investigated a wide range of visual hand representations. For instance, Knierim et al. [12] conducted a typing experiment in VR and found that using semi-transparent hands resulted in higher performance for inexperienced typists. Similarly, Grubert et al. [5] showed that opaque hand avatars reduce typing performance in VR. Veldhuizen et al. [22] further demonstrated that

semi-transparent hands outperform opaque hands in a VR manipulation task.

Hatira et al. [9] investigated transparent and invisible hand representations in VR sorting and navigation tasks and found that increasing hand transparency led to improved placement accuracy compared to opaque hands. Taken together, these findings suggest that reducing visual interference introduced by virtual hand avatars can improve accuracy in tasks that require precise spatial alignment. Moreover, Ocampo et al. [18] showed that the presence of a visual avatar can improve accuracy in target acquisition tasks when using hand tracking, even when the avatar does not perfectly match the input modality, highlighting the importance of visual feedback for accurate interaction.

Voisard et al. [24] systematically examined opaque, transparent, and invisible hand visualizations in VR across different movement phases, including reaching, grasping, transporting, and inserting. Their results showed that the effectiveness of hand visualization strongly depends on the current movement phase, with invisible hands leading to higher motor accuracy during insertion. Building on this observation, Turkmen et al. [21] introduced adaptive hand visualization techniques in a VR-based Pedicle Screw Placement (PSP) task. Their findings demonstrated that dynamically adapting hand visibility based on movement context improves placement accuracy and user experience compared to static opaque hand representations. However, these studies were conducted exclusively in VR, leaving open the question of whether such adaptive techniques are equally effective in AR.

In contrast to VR, fewer studies have examined hand visualization in AR. Normand et al. [17] investigated visual and visuo-haptic hand rendering techniques for AR manipulation tasks, comparing multiple visual hand representations combined with vibrotactile feedback. Their results indicated that visual hand renderings provide useful feedback for hand tracking, but their perceived necessity decreases when haptic feedback is available. However, their study did not focus on accuracy-critical manipulation tasks.

Recent work by DeMarbre et al. [3] compared hand, controller, combined, and no visual representations across both VR and mixed reality (MR) selection tasks. Their results showed comparable objective performance between VR and MR, but revealed differences in subjective perception. In MR, participants preferred having no visual representation, reporting that overlaid virtual hands or controllers felt duplicated or distracting when combined with their real hands. These findings further highlight that visual representations beneficial in VR may not directly translate to AR or MR, and that minimizing redundant visual overlays can improve user experience in mixed reality environments. Hartbrich et al. [8] examined the effects of hand visibility in AR manipulation tasks involving both real and virtual objects. Their results showed that manipulation performance is higher when interacting with real objects, that invisible hand avatars lead to fewer errors in fine manipulation tasks with real objects, and that users prefer visible hand representations when interacting with virtual objects. While their study included a fine manipulation task where accuracy is important, it did not investigate adaptive hand visualization techniques in AR.

2.2 Pedicle Screw Placement

Pedicle Screw Placement (PSP) is a commonly used procedure in spinal surgery, where accurate alignment and placement are essential to avoid complication [26]. Due to its high demands on fine motor control and spatial accuracy, PSP has been widely adopted as a benchmark task in both VR and AR research, particularly in studies investigating surgical guidance and training systems [27, 29, 28, 14].

Prior work has demonstrated the potential of immersive technologies to support PSP by improving placement accuracy and reducing errors. For example, AR-based approaches have been shown

to provide effective visual guidance for screw placement, achieving performance comparable to traditional planning tools [2, 29]. Similarly, VR-based simulators have been found to improve placement accuracy and success rates compared to conventional training methods [27]. Lastly, Turkmen et al. [21] used PSP task to evaluate effect of hand visibilities in VR and they found that adaptive hand visibilities improve the accuracy compared to opaque hands. These studies establish PSP as a realistic and reproducible task for evaluating accuracy in immersive environments.

Using the fine motor and accuracy demands of the PSP task, we aim to better understand the role of hand visualization design in supporting accurate interactions beyond the medical domain.

3 MOTIVATION & HYPOTHESES

Most existing hand visualization techniques in immersive environments are designed as static solutions, treating interaction as a single, uniform process. However, interaction in XR typically consists of distinct phases (reaching, grasping, transporting and inserting), each with different perceptual and motor demands. Recent work [24] suggests that hand visibility requirements vary across these phases, motivating adaptive visualization approaches in VR. While this observation has motivated adaptive hand visualization techniques in VR (e.g., [21]) the effectiveness in AR has not been investigated.

AR involves the simultaneous perception of real-world objects and virtual content, which increase visual complexity and potential occlusion. These differences may change how hand visibility affects performance, particularly in tasks requiring high accuracy. This motivates an investigation of adaptive hand visualization techniques in AR and their impact on user performance and experience.

To address this gap, we investigate adaptive hand visualization techniques in AR that dynamically adjust hand visibility according to the current hand movement. Specifically, we study two adaptive approaches: POSITION-BASED visualization, which changes hand visibility based on the hand's proximity to interaction-critical elements, and SPEED-BASED visualization, which adapts visibility based on hand movement speed following an approach explored in prior work [21].

Based on prior findings in VR and the unique perceptual challenges of AR, we formulate the following hypotheses:

H1 *Compared to static hand visualizations (OPAQUE, TRANSPARENT, and INVISIBLE), adaptive hand visualizations (POSITION-BASED and SPEED-BASED) lead to improved task performance, as measured by placement accuracy and task completion time.*

H2 *Adaptive hand visualizations improve user experience in AR, as reflected by participants' feedback compared to static hand visualizations (OPAQUE, TRANSPARENT, and INVISIBLE).*

4 EXPERIMENTAL DESIGN

4.1 Participants

We conducted a user study with 15 participants (8 male and 7 female) aged between 21 and 32 (Mean = 25.13 ± 2.39) from the local university. Fourteen were right-handed and one left-handed. All participants reported normal or corrected-to-normal vision. When asked about how many times they had experienced AR previously, one participant reported never, six reported 1-3 times, three reported 3-5 times, and six participants reported more than 5 times.

4.2 Apparatus

We used a 13th Gen Intel(R) Core(TM) i9-13900KF at 5.8 GHz, 32 GB RAM desktop PC with an NVIDIA GeForce RTX 4070 graphics card. We used an Oculus Quest Pro HMD and Unity3D version 2022.3.49 to design and implement the virtual objects.

4.3 Procedure

Upon arrival, participants were asked to provide informed consent and complete a demographic questionnaire. The experimenter then introduced the study, explained the AR setup, and described the Pedicle Screw Placement (PSP) task and the overall procedure.

In the PSP task, participants were instructed to insert a virtual pedicle screw into a predefined target location indicated by an orange outline (Figure 2). The target locations were derived from a 3D spine model used during system development to define anatomically plausible insertion points; however, the 3D spine itself was not visible to participants during the experiment. Target positions were selected *a priori* following an established task design previously used in VR based PSP study [21] to ensure consistency and comparability. Participants were instructed to perform the task "as quickly and accurately as possible."

During the experiment, participants were seated. In the AR scene, they were positioned facing the PSP task (Figure 1(a)). Participants performed the PSP task using five different hand visualization conditions: OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED, and POSITION-BASED. All conditions were performed using the dominant hand. For each hand visualization condition, participants were asked to place ten screws, resulting in ten repetitions per condition.

4.4 Hand Visibilities

To assess participants' accuracy, we adopted the same movement phase definitions as in prior work [23, 24, 21]. The task was decomposed into four sequential movement phases: *Reaching*, *Grasping*, *Transporting*, and *Inserting*. The *Reaching* phase refers to the period during which participants moved their hand toward the target screw without holding any object (Figure 1(b)). This phase started at the beginning of each repetition and ended when the hand reached the screw. The *Grasping* phase began immediately after the reaching phase and lasted until the participant successfully picked up the pedicle screw (Figure 1(c)). Once the screw was grasped, the *Transporting* phase started and continued while the participant moved the screw toward the highlighted target area (Figure 1(d)). Finally, the *Inserting* phase began when the hand reached the highlighted target area and ended when the participant confirmed the final placement by pressing the space bar on the keyboard (Figure 1(e)).

We conducted the experiment with five different hand visibilities ($V =$ OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED, POSITION-BASED) to assess the effect of hand visualizations on user performance.

Following prior work [21], we implemented adaptive hand visibility to two scenarios SPEED-BASED and POSITION-BASED. In both scenarios, the hand visibility is phase-dependent: the hand is OPAQUE during reaching, becomes TRANSPARENT during grasping and transporting, and is INVISIBLE during inserting as shown in Figure 1.

For scenarios where interactive objects and target regions are not predetermined, we employed a SPEED-BASED hand visualization, in which hand visibility dynamically adapts based on movement speed and movement phase. This approach uses hand speed to identify task phase, allowing the hand to be most visible during reaching and gradually reducing visibility during grasping and transporting phases and then becoming totally invisible during inserting phase where accuracy is important.

When interactive objects and target regions were known in advance, we use a POSITION-BASED hand visualization that adapts hand visibility based on the hand's spatial proximity to interaction-critical elements. In this case, hand transparency changes smoothly as the hand approaches the target region, becoming invisible during insertion. Distance thresholds were selected to match those used in prior work [24] to ensure comparability across studies.

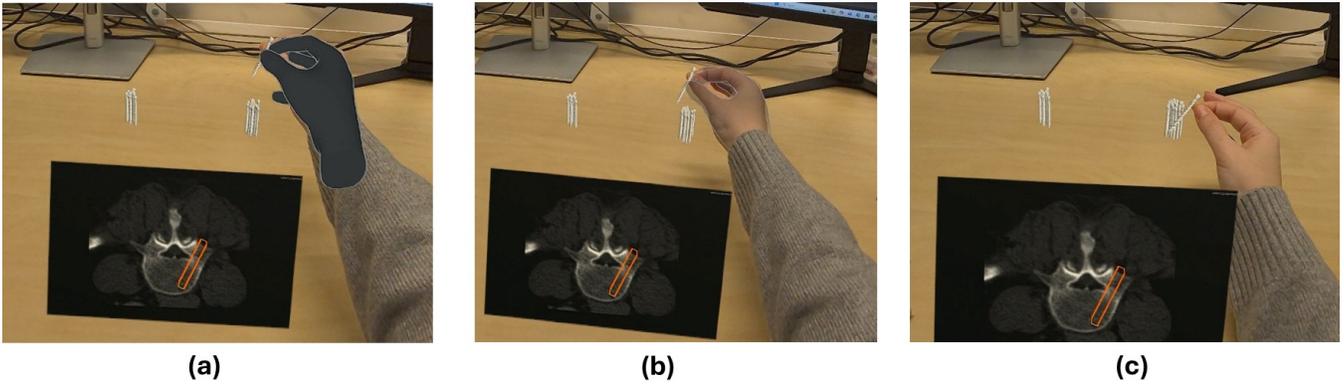


Figure 2: Hand visibilities during Pedicle Screw Placement (PSP): a) OPAQUE, b) TRANSPARENT and c) INVISIBLE hands.

Unlike the VR study by Turkmen et al.[21], where the invisible condition removes all hand representations, our AR implementation removes only the virtual hand avatar. The user’s real hands remain visible in all conditions; in the OPAQUE and TRANSPARENT conditions, the avatar is rendered on top of the real hand, while in the INVISIBLE condition participants are still able to see their real hands, similar to a previous AR study [8].

4.5 Experimental Design & Evaluation Metrics

We used a 5×10 within-subject design with five visibility techniques ($5_V =$ OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED, and POSITION-BASED). For each condition, participants were asked to place 10 screws, leading to 10 repetitions (10_{Rep}) for per condition. This design yielded a total of 50 trials ($5_V \times 10_{Rep}$) per participant. Hand visibility conditions were counter-balanced across participants using a Latin-square design to compensate for learning effects.

During the experiment, we recorded the following parameters for each movement: duration (s), overlap (%), error angle ($^\circ$), and distance (cm).

Duration (s) refers to the total time taken to complete a each movement phase and is measured from the start to the end of phase.

Overlap (%) measures how much of the object is placed inside the target area at the end of the Insert sub-task. It quantifies the alignment ratio between the volume of the placed virtual screw and the highlighted target volume.

Error angle ($^\circ$) measures the absolute upward direction (local up vector) of the inserted screw and the highlighted target area. This measurement evaluates how accurately participants aligned the screw’s orientation with the intended target area.

Error distance (cm) represents the Euclidean distance between the center of the highlighted target area on the spine image and the center of the placed screw. This metric is recorded at the end of each insertion task.

5 RESULTS

The data was pre-processed and plotted through JMP software. Data analysis was done using one-way repeated measures (RM) ANOVA using SPSS 31. The data was considered normally distributed if the Skewness (S) and Kurtosis (K) values were within ± 1 [6, 16]. Otherwise, we used log-transform before ANOVA. If the data were not normally distributed after the log transform, we used Aligned Rank Transformation (ART) [25] on the original data before ANOVA. For post hoc analyses, we conducted pairwise comparisons using paired t-tests with Bonferroni correction and applied the Huynh-Feldt correction when $\epsilon < 0.75$. For the data where ART was used, we applied ART-C for the post hoc analyses.

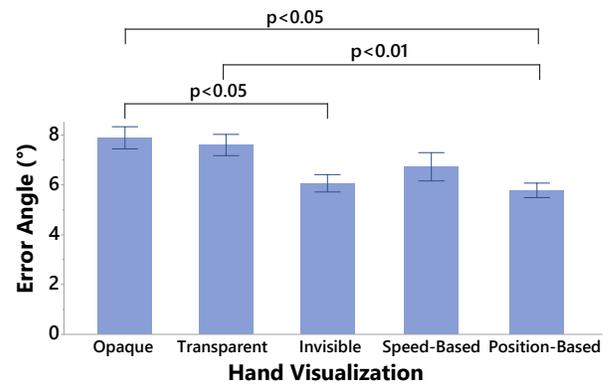


Figure 3: Post Hoc comparison of Error Angle across different Hand Visibility conditions (OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED, and POSITION-BASED).

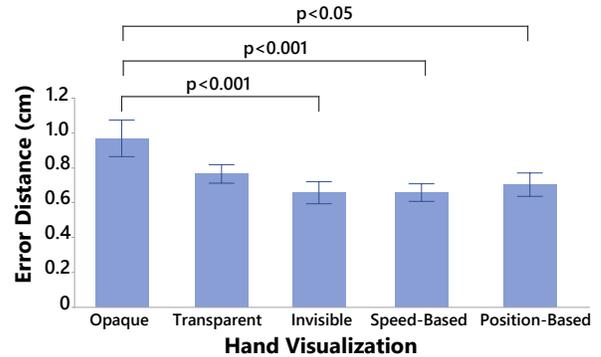


Figure 4: Post Hoc comparison of Error Distance across different Hand Visibility conditions (OPAQUE, TRANSPARENT, INVISIBLE, SPEED-BASED, and POSITION-BASED).

Duration (S=0.7150; K=-0.1322) and Error Angle (S=0.4055; K=-0.1944) data were normally distributed. Overlap and Error Distance data were not normally distributed, even after applying the log-transform, so we applied ART before the analysis.

Duration (s). We did not find a significant main effect of hand visibility on duration ($F_{4,56} = 1.043, p = .393, \eta^2 = .069$).

Error Angle (deg). We found a significant main effect of hand visibility on error angle ($F_{4,56} = 4.965, p = .002, \eta^2 = .262$). Post hoc results (Figure 3) show that POSITION-BASED hand visibility resulted in lower error angles compared to OPAQUE and TRANSPARENT. Moreover, INVISIBLE hands also reduced error angles compared to OPAQUE hands.

Error Distance (cm). Effect of hand visibility on error distance was significant ($F_{4,56} = 8.95, p < .001, \eta^2 = .39$). Post hoc results (Figure 4) show that POSITION-BASED had lower error distances than OPAQUE ($p = .011$). SPEED-BASED had lower error distances compared to OPAQUE ($p < .001$). Lastly, INVISIBLE resulted in lower error distances than OPAQUE ($p = .002$).

Overlap (%). We did not find a significant main effect of hand visibility on overlap ($F_{4,56} = 0.941, ns, \eta^2 = .014$).

Subjective Feedback. We asked participants which hand visibility they would prefer most and why. Five participants preferred POSITION-BASED and P12 commented as *“It felt the most supportive one during the placement”*. P14 mentioned that *“I would like to see hand avatars during the overall interaction and while inserting, as it turns invisible, it makes it easier to place screws accurately”*. Five participants preferred INVISIBLE hands, and P4 commented as *“I don’t like to see any hand avatars in AR, it looks extra and distracting”*. Three participants preferred SPEED-BASED and P9 commented as *“I liked to have a control over the hand opacity with my hand speed”*. Lastly, one participant preferred OPAQUE and one preferred TRANSPARENT. P1 commented on OPAQUE: *“It overlays over my real hands so it helps me to consider my movements based on the avatar hand, not my real hands”* and P10 stated *“It was more comfortable to see my hands and other objects as well”*.

6 DISCUSSION

Our findings provide insights into the effect of adaptive hand visibility in AR Pedicle Screw Placement task which require high accuracy. The significant effects observed for error angle and error distance indicate that hand visibility design directly influences placement accuracy in AR. In line with prior VR findings [22, 24, 9, 21], conditions that reduced hand visibility led to more accurate screw placement than OPAQUE hands. This suggests that visual occlusion introduced by fully opaque hand avatars remains a challenge in AR.

Yet, in AR, reducing hand visibility does not imply removing the user’s hand entirely from view. Unlike VR, where INVISIBLE hands result in the complete absence of hand representation, AR users continue to see their real hands even when the virtual hand avatar becomes invisible. As a result, INVISIBLE and adaptive hand visibility (SPEED-BASED and POSITION-BASED) conditions primarily reduce the visual interference caused by rendering a virtual hand avatar on top of the user’s real hand. This distinction aligns with prior AR findings showing that users often prefer not to see a virtual hand avatar over their real hands during manipulation tasks [8].

Our results partially support **H1** by showing that adaptive hand visibility techniques can improve placement accuracy in AR. While INVISIBLE hands reduced error angle compared to OPAQUE hands, POSITION-BASED visibility reduced error angles compared to OPAQUE and TRANSPARENT hand visibilities. In AR, users simultaneously perceive physical objects, virtual overlays, and their own real hands, resulting in increased perceptual complexity compared to VR. By linking the disappearance of the *virtual hand avatar* to spatial proximity to the insertion target, POSITION-BASED visibility provides a predictable and meaningful cue that aligns with users’ expectations: the avatar disappears only when accuracy is required during the inserting phase. In addition to objective performance benefits, subjective feedback provides partial support for **H2**. Participants described the position-based condition as *“supportive during placement,”* suggesting that the visibility transitions were per-

ceived as stable, well-timed, and helpful during accuracy-critical interaction.

Moreover, SPEED-BASED visibility also reduced error distance compared to OPAQUE hands, further supporting **H1**. This indicates that adapting hand visibility based on movement speed can support accuracy by aligning visibility changes with users’ motor intent. When users naturally slow down to insert the screw, the hand fades out. Subjective feedback provides partial support for **H2**. Participants who preferred SPEED-BASED visibility emphasized the sense of control it afforded, noting that changes in hand opacity closely followed their hand movement speed. This suggests that speed-based adaptation may be particularly suitable for users who prefer implicit control over hand visibility. However, in AR, where hand speed can vary due to factors unrelated to task intent (e.g., hesitation, environmental constraints), speed-based transitions may be less predictable than spatially defined adaptations, which can explain why this condition is less preferred by participants compared to POSITION-BASED and INVISIBLE hands.

These findings indicate that fully removing the virtual hand avatar throughout the interaction, as in INVISIBLE hands, is not necessary; instead, selectively reducing hand visibility during accuracy-critical movement can improve performance in a better way, which is also supported by subjective feedback. This observation aligns with findings from previous VR work [24, 21], who showed that different movement phases benefit from different hand representations, and our work demonstrates that this principle also applies to AR.

Contrary to **H1** with respect to task completion time, we did not observe significant effects of hand visibility on execution speed. This suggests that adaptive hand visibility primarily influences placement accuracy rather than movement speed, which aligns with the design goal of supporting accurate interaction rather than encouraging faster execution. Similarly, the absence of significant differences in overlap indicates that this metric may be less sensitive to variations in hand visibility. Overlap primarily captures whether the screw is positioned within the target volume, rather than reflecting finer aspects of alignment such as orientation or positional accuracy, which were more strongly affected by hand visibility.

Taken together, our findings suggest that adaptive hand visibility techniques can effectively support accurate tasks in AR. The POSITION-BASED visibility condition appears particularly well-suited for AR scenarios involving predefined targets. In contrast, speed-based adaptation may be better suited for open-ended tasks where targets are not known in advance and where users prefer movement-driven control. Our results demonstrate that adaptive hand visibility techniques developed for VR can translate to AR, but must account for the additional perceptual complexity introduced by real-world context. Designers of AR systems should therefore consider not only whether to reduce hand visibility, but also how visibility transitions are triggered and perceived by users during different phases of interaction.

Finally, We note several limitations of this study. Although participants did not report physical fatigue, repeated exposure to the task may have introduced learning effects across conditions, despite counter-balancing condition order. Future work could further mitigate these effects by giving additional breaks and randomizing trials within each condition. Addressing these limitations will help strengthen the generalizability of our findings.

7 CONCLUSION

This work investigated whether adaptive hand visibility techniques, previously shown to be effective in VR, are also effective in AR. Using an AR-based pedicle screw placement task, we compared commonly used static hand visualizations with two adaptive approaches that dynamically adjust hand visibility based on movement phase.

Our results show that hand visibility design significantly af-

fects placement accuracy in AR. In particular, adaptive techniques that reduce virtual hand avatar visibility during accuracy-critical movement phases improved placement accuracy compared to fully opaque hands. Among the evaluated techniques, POSITION-BASED visibility consistently resulted in the lowest placement errors, suggesting that spatially grounded adaptation provides predictable and meaningful support in AR environments with predefined targets. While SPEED-BASED visibility also improved accuracy and was preferred by some users due to its movement speed-driven control, its effectiveness appeared more sensitive to variations in user behavior and task context.

Overall, our findings suggest that selectively adapting hand visibility—rather than fully removing hand representations—offers an effective balance between visual guidance and reduced occlusion in AR. Although AR differs from VR in that user’s real hands remain visible which potentially increase perceptual complexity, our results extend prior VR findings to AR where adaptive hand visualization techniques remain beneficial in AR. This work provides evidence that adaptive hand visibility techniques can support accuracy-demanding tasks in AR and offers guidance for designing future AR systems where accurate interaction is critical.

REFERENCES

- [1] G. Buckingham. Hand tracking for immersive virtual reality: Opportunities and challenges. *Frontiers in Virtual Reality*, 2, 2021. 1
- [2] A. P.-D. de-la Lastra, T. Ungi, D. Morton, G. Fichtinger, and J. Pascau. Real-time integration between microsoft hololens 2 and 3d slicer with demonstration in pedicle screw placement planning. *International Journal of Computer Assisted Radiology and Surgery (Int J CARS)*, 18:2023–2032, 2023. 3
- [3] E. DeMarbre, J. Henderson, J. F. Gonzalez, and R. J. Teather. Effects of virtual controller representation and virtuality on selection performance in extended reality. In *ACM Symposium on Virtual Reality Software and Technology*. Association for Computing Machinery, 2025. 2
- [4] A. L. Dwarkadas, R. Krishna Challa, V. Talasila, and S. K. G. Augmented/virtual reality: Technological advancement with use cases. In *Global Conference on Information Technologies and Communications*, pages 1–7, 2023. 1
- [5] J. Grubert, L. Witzani, E. Ofek, M. Pahud, M. Kranz, and P. O. Kristensson. Effects of hand representations for typing in virtual reality. In *IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 151–158, 2018. 2
- [6] J. F. Hair Jr, W. C. Black, B. J. Babin, and R. E. Anderson. *Multivariate data analysis*, 2014. 4
- [7] A. Hameed, A. Perkis, and S. Möller. Evaluating hand-tracking interaction for performing motor-tasks in vr learning environments. In *International Conference on Quality of Multimedia Experience (QoMEX)*, 2021. 1
- [8] J. Hartbrich, S. A. Arboleda, S. Göring, and A. Raake. The effect of hand visibility in ar: Comparing dexterity and interaction with virtual and real objects. *IEEE Transactions on Visualization and Computer Graphics*, 31(11):10026–10034, 2025. 2, 4, 5
- [9] A. Hatira, Z. E. Gelmez, A. U. Batmaz, and M. Sarac. Effect of hand and object visibility in navigational tasks based on rotational and translational movements in virtual reality. In *IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pages 115–125, 2024. 2, 5
- [10] N. Jamalian, M. Gillies, F. F. Leymarie, and X. Pan. The effects of hand tracking on user performance: an experimental study of an object selection based memory game. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 2022. 1
- [11] C. Khundam, V. Vorachart, P. Preeyawongsakul, W. Hosap, and F. Noël. A comparative study of interaction time and usability of using controllers and hand tracking in virtual reality training. *Informatics*, 8(3), 2021. 1
- [12] P. Knierim, V. Schwind, A. M. Feit, F. Nieuwenhuizen, and N. Henze. Physical keyboards in virtual reality: Analysis of typing performance and effects of avatar hands. In *ACM CHI Conference on Human Factors in Computing Systems*, page 1–9. Association for Computing Machinery, 2018. 2
- [13] S. Kumari and N. Polke. Implementation issues of augmented reality and virtual reality: A survey. In J. Hemanth, X. Fernando, P. Lafata, and Z. Baig, editors, *International Conference on Intelligent Data Communication Technologies and Internet of Things (ICICI) 2018*, pages 853–861. Cham, 2019. Springer International Publishing. 1
- [14] H. Li, P. Zhang, G. Wang, H. Liu, X. Yang, G. Wang, and Z. Sun. Real-time navigation with guide template for pedicle screw placement using an augmented reality head-mounted device: A proof-of-concept study. *Journal of Orthopaedics and Traumatology (JOIO)*, 57:776–781, 2023. 2
- [15] J.-L. Lugin, M. Wiedemann, D. Bieberstein, and M. E. Latoschik. Influence of avatar realism on stressful situation in vr. In *IEEE Virtual Reality (VR)*, 2015. 1
- [16] P. Mallery and D. George. *SPSS for windows step by step: a simple guide and reference*. Allyn, Bacon, Boston., 2003. 4
- [17] E. Normand, C. Pacchierotti, E. Marchand, and M. Marchal. Visuo-haptic rendering of the hand during 3d manipulation in augmented reality. *IEEE Transactions on Haptics*, 17(2), 2024. 2
- [18] N. Ocampo, J. F. Gonzalez, and R. J. Teather. Comparing Hand and Controller Avatars with Hand Tracking and Controller-Based Interaction. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 164–174, Los Alamitos, CA, USA, 2025. IEEE Computer Society. 2
- [19] M. Prachyabrued and C. W. Borst. Design and evaluation of visual interpenetration cues in virtual grasping. *IEEE Transactions on Visualization and Computer Graphics*, 22(6):1718–1731, 2016. 1
- [20] M. Shanmugam, M. Sudha, K. Lavitha, V. P. Venkatesan, and R. Keerthana. Research opportunities on virtual reality and augmented reality: a survey. In *IEEE International Conference on System, Computation, Automation and Networking (ICSCAN)*, pages 1–6, 2019. 1
- [21] R. Turkmen, L. Voisard, M. Kersten-Oertel, and A. U. Batmaz. Adaptive hand visibility for accurate 3d user interactions in virtual environments. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 12–22, 2025. 1, 2, 3, 4, 5
- [22] M. Van Veldhuizen and X. Yang. The effect of semi-transparent and interpenetrable hands on object manipulation in virtual reality. *IEEE Access*, 9, 2021. 2, 5
- [23] O. Vasylenko, M. M. Gorecka, and C. Rodríguez-Aranda. Manual dexterity in young and healthy older adults. 1. age- and gender-related differences in unimanual and bimanual performance. *Developmental Psychobiology*, 60(4):407–427, 2018. 2, 3
- [24] L. Voisard, A. Hatira, M. Sarac, M. Kersten-Oertel, and A. U. Batmaz. Effects of opaque, transparent and invisible hand visualization styles on motor dexterity in a virtual reality based purdue pegboard test. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 2023. 2, 3, 5
- [25] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins. The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures. In *ACM SIGCHI Conference on Human Factors in Computing Systems*, pages 143–146. ACM, 2011. 4
- [26] S.-X. Xiao, W.-T. Wu, T.-C. Yu, I.-H. Chen, and K.-T. Yeh. Augmenting reality in spinal surgery: A narrative review of augmented reality applications in pedicle screw instrumentation. *Medicina*, 60(9), 2024. 2
- [27] B. Xin, X. Huang, W. Wan, K. Lv, Y. Hu, J. Wang, S. Li, W. Zou, J. Xiao, and T. Liu. The efficacy of immersive virtual reality surgical simulator training for pedicle screw placement: a randomized double-blind controlled trial. *International Orthopaedics (SICOT)*, 44:927–934, 2020. 2, 3
- [28] T. Yamout, L. D. Orosz, C. R. Good, E. Jazini, B. Allen, and J. L. Gum. Technological advances in spine surgery: Navigation, robotics, and augmented reality. *Orthopedic Clinics of North America*, 54(2):237–246, 2023. 2
- [29] S. Youssef, J. M. McDonnell, K. V. Wilson, L. Turley, G. Cunniffe, S. Morris, S. Darwish, and J. S. Butler. Accuracy of augmented reality-assisted pedicle screw placement: a systematic review. *European Spine Journal*, 33:974–984, 2024. 2, 3