Virtual Throwing as a Method to Evaluate Distance Perception in Virtual Reality

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***Abstract*—Accurate distance perception is critical for interaction within immersive virtual environments (IVEs). However, numerous studies have shown that users consistently underestimate egocentric distances in virtual reality (VR) due to degraded or ambiguous visual cues. Techniques such as blind walking and virtual object throwing have been used to measure this perceptual bias, consistently revealing an underestimation of around 30%. Attempts to correct this distortion, including geometric warping methods using warp multipliers, have yielded mixed results. With recent technological advancements, users can now perform simulated throwing within VR using controllers, allowing for real-time visual feedback. Nevertheless, throwing accuracy remains significantly lower in VR compared to the physical world, largely due to the lack of haptic feedback and the challenge of precisely timing object release. To address this issue, we propose a multimodal haptic solution that combines variable-weight wristbands with vibrotactile feedback at the moment of release. This design aims to improve the user's proprioception and control during virtual throwing tasks. This study investigates whether such haptic augmentation can enhance motor accuracy and distance estimation in VR, potentially reducing the perceptual gap between real and virtual environments.**

When observing a target in space, the human brain relies on multiple visual cues to estimate distance, including binocular disparity, motion parallax, texture gradients, and familiar size [1, 2]. These cues typically provide reliable information in the physical world. However, in virtual environments—especially those with low detail or artificial rendering—such cues can become ambiguous or degraded. Head-mounted displays (HMDs) introduce specific limitations such as reduced field of view, mismatched accommodation-vergence responses, and impoverished motion or texture cues. Consequently, distance perception in virtual reality (VR) often diverges significantly from perception in the real world. This misperception of egocentric distances poses challenges for natural interaction, navigation, and task performance in immersive virtual environments (IVEs).

To assess this phenomenon, various experimental methods have been developed. One standard approach is *blind walking*, where participants view a target in VR, remove the headset, and attempt to walk to its remembered location. Another method involves throwing an object at the virtual target. To reduce variability, the throw is typically performed in an upward arc. Both methods have yielded consistent results: distances in VR are underestimated by roughly 30% [3]. These findings align with broader evidence of spatial compression in virtual space [4].

Efforts to compensate for this bias have included geometric correction techniques. In particular, the use of a shader-based warping function—defined by a *warp multiplier*—has been explored to adjust perceived object positions [5]. However, the effectiveness of this method has been limited. For instance, a warp multiplier of 1.4, which theoretically should yield a 40% correction, only resulted in a 14% improvement, highlighting the complexity of perceptual recalibration in VR.

Since [3] was published in 2005, VR hardware and interaction techniques have evolved substantially. Virtual throwing can now be fully simulated using handheld controllers equipped with motion tracking and triggers. This allows for more precise studies of motor behavior and perceptual feedback. Nonetheless, accuracy in virtual throwing remains lower than in real-world tasks. According to [6], users are about twice as inaccurate in VR, even after training. This performance gap is attributed to difficulties in timing the trigger release and the absence of tactile cues that would typically inform the thrower of the object's weight and center of mass.

These limitations underline the importance of haptic feedback in enhancing motor control in VR. Previous studies have shown that proprioceptive mismatches and the lack of tactile realism can reduce task performance [7]. In this study, we propose a novel haptic augmentation method involving variable-weight wristbands and vibrotactile feedback synchronized with the release moment. By simulating both mass and tactile confirmation, we aim to improve throwing precision and depth perception in VR. Our hypothesis is that this multisensory feedback will reduce the discrepancy between real and virtual performance, thereby improving user experience and interaction fidelity.

OBJECTIVES AND RESEARCH HYPOTHESES

Research Question

How does haptic feedback—through added mass and vibrotactile stimulation—shape proprioception and perceived effort to improve throwing precision and distance perception in AR scenarios?

Objectives

- Verify that tactile cues (mass and vibration) attenuate the characteristic distance-compression bias observed in a purely visual virtual-throwing baseline.
- Quantify the respective and joint effects of mass and vibration on release-point precision and projectile-trajectory estimation.

Hypotheses

- $\mathbf{H_1}$: The introduction of a handheld mass and/or vibrotactile stimulation reduces distance-estimation error relative to the visual-only condition.
- $\mathbf{H_2}$: The simultaneous application of mass and vibration produces a supra-additive improvement, attributable to the synergistic reinforcement of proprioceptive cues.

EXPERIMENTAL PROTOCOL

Sample — Twenty right-handed participants (aged 20–35) completed all eight experimental conditions following a Latin-square order, ensuring balanced carry-over and maximised statistical power.

Conditions —Each participant performed 3 throws per condition at three target distances (4, 7, and 12 m), with a 15 s interval between throws:

- *Control*: no added mass, no vibration.
- *Vibration*: 10 Hz/1 mm (V1) and 20 Hz/2 mm (V2).
- *Mass*: 100 g, 200 g masses attached to a velcro bracelet.
- *Combined*: 100 g + V1, 200 g + V2.

Each throw lasted approximately 15 s (setup, execution, record), totalling about 15 minutes per participant including breaks.

Error Metric — Primary outcome is Euclidean distance between impact and target, averaged over throws per condition.

Complementary Measures — A blind-walking transfer test assessed cross-task distance perception; post-session interviews captured subjective effort and realism.

Experiments

Experimental Setup

Participants wore an Oculus Quest 2 headset connected to the experiment computer and interacted using a Quest 2 controller (154 g) along with two Velcro bracelets (100 g each). The bracelets were attached to the participants' wrists when required, using their Velcro straps. All software ran at 90 FPS, recording 6-DoF hand poses and projectile trajectories. Participants were immersed in a Unity scene covering 400 m^2.

FIGURE 1: Experimental setup: wrist equipped with a single Velcro bracelet (100 g) and Oculus Quest 2 controller.

FIGURE 2: Close-up view of the 100 g Velcro bracelets before mounting.

Statistical Analysis and Results

We analysed the absolute throwing errors across 8 experimental conditions (Control, 10 Hz, 20 Hz, 50 g, 100 g, 200 g, 50 g + 10 Hz, 100 g + 20 Hz) and 3 target distances (4 m, 7 m, 12 m). For each subject ($n = 20$), the mean absolute error was computed per condition and distance.

Before comparing the conditions, we tested whether the error data followed a normal distribution. This was done using the **Shapiro–Wilk test**, which evaluates whether the distribution of a sample is close to normal. Its formula is:

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

Here, $x_{(i)}$ are the ordered values, $\bar{x}$ the sample mean, and a_i constants derived from expected order statistics under normality. Since none of the condition×distance groups showed $p > 0.05$, we could not assume normality and therefore adopted non-parametric tests.

To test whether condition had an overall effect, we used the **Friedman test** at each distance. It compares the rankings of values across conditions within subjects, and its test statistic is:

$$\chi_F^2 = \frac{12}{nk(k+1)} \sum_{j=1}^{k} R_j^2 - 3n(k+1)$$

where n is the number of subjects, k the number of conditions, and R_j the total rank for condition j.

We opted for the Friedman test instead of a repeated-measures ANOVA because our error distributions were non-normal (Shapiro–Wilk $p < 0.05$), making the non-parametric Friedman test more reliable for detecting condition effects.

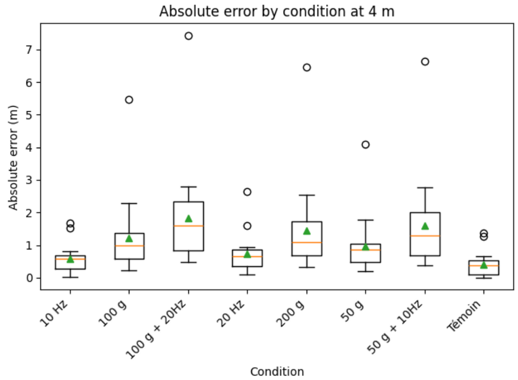
If the Friedman test was significant, we performed follow-up comparisons using the **Wilcoxon signed-rank test**, which compares paired samples by ranking absolute differences. For example, to compare condition A vs. B, we take each participant's error difference (A−B), rank its absolute values, then sum positive and negative ranks to compute W.

Because there are 28 (i.e. eight choose two) pairwise tests per distance, we applied a **Bonferroni correction** to control the family-wise error rate:

$$\alpha_{\text{adj}} = \frac{\alpha}{m}$$

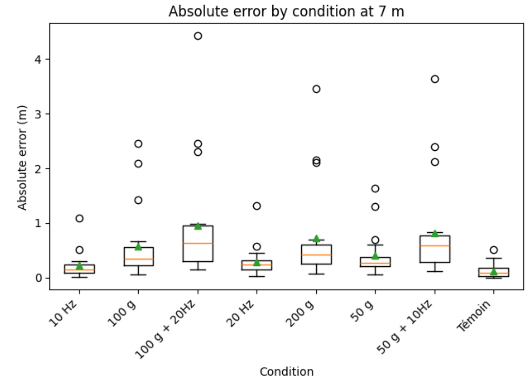
with $\alpha = 0.05$ and $m = 28$, thus only $p < 0.0018$ are considered significant.

Visual results. Figures 3 and 4 summarize the full error distributions and mean ± SEM across all conditions and distances.



(a) Absolute error at 4 m

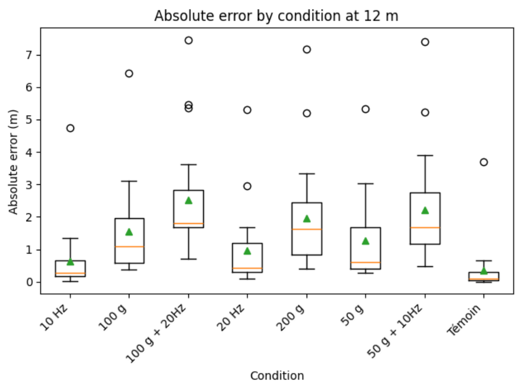
Error rises progressively from Control → vibration → mass → combined cues.



(b) Absolute error at 7 m

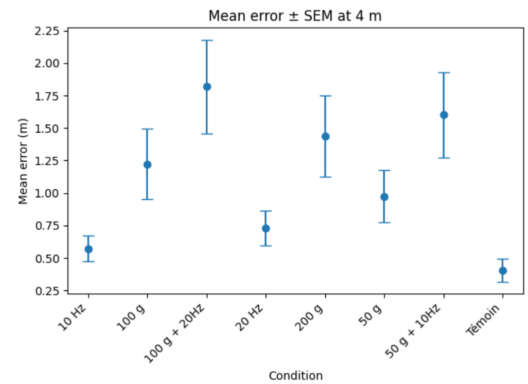
Similar pattern at 7 m, with combined cues exhibiting the greatest variability.

FIGURE 3: Boxplots of absolute error by condition at short distances.



(a) Absolute error at 12 m

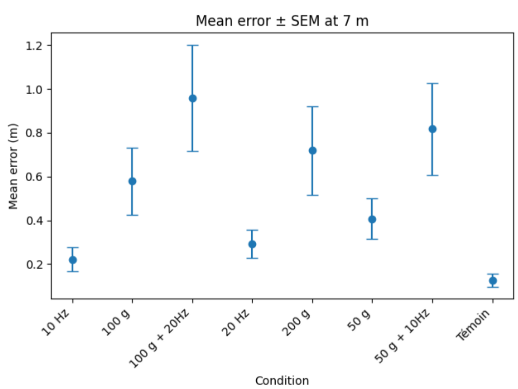
At 12 m, the combined mass+vibration condition shows the highest median error and spread.



(b) Mean error ± SEM at 4 m

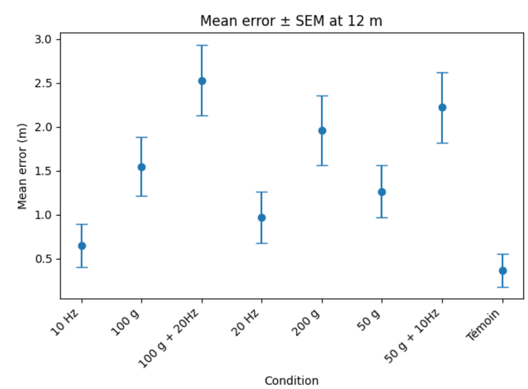
Mean errors confirm the ranking: combined → mass → vibration → Control.

FIGURE 4: Error distributions at longest distance and group means with SEM at 4 m .



(a) Mean error ± SEM at 7 m

Increased SEM for heavier and combined cues at mid-range.



(b) Mean error ± SEM at 12 m

Highest inter-subject variability in the 100 g + 20 Hz condition.

FIGURE 5: Mean absolute error±SEM across longer distances.

Inferential results. The Friedman test revealed a significant effect of condition at all distances:

- 4 m: $\chi^2(7) = 132.68$, $p < 0.001$
- 7 m: $\chi^2(7) = 132.46$, $p < 0.001$
- 12 m: $\chi^2(7) = 132.76$, $p < 0.001$

Wilcoxon post-hoc tests with Bonferroni correction showed that virtually every pairwise comparison was significant ($p_{\text{adj}} < 0.01$), confirming that mass, vibration, and combined manipulations all robustly affected performance relative to Control.

Discussion and Participant Feedback

Our results show that both mass and vibrotactile cues significantly affect virtual-throwing accuracy, with combined cues producing the largest errors and greatest variability. The Friedman tests confirmed a robust effect of condition at all distances (4 m: $\chi^2(7) = 132.68$, 7 m: $\chi^2(7) = 132.46$, 12 m: $\chi^2(7) = 132.76$, all $p < 0.001$), and nearly every Wilcoxon pairwise comparison remained significant after Bonferroni correction ($p_{\text{adj}} < 0.01$).

The largest errors appeared under combined mass+vibration conditions, suggesting a supra-additive interference: heavy weights may overload proprioceptive estimations of release force, while concurrent vibrations can disrupt the temporal cueing of the throw. In contrast, light vibration alone (10 Hz) produced minimal error increases, indicating that low-intensity haptic feedback can augment timing without substantially distorting force judgments.

These findings align with Auffret et al. (2020), who reported that added controller mass increases release timing variability, and with Leadbetter et al. (2005), who observed similar under-estimation trends in real-world throwing. Our work extends these insights by demonstrating that vibrotactile cues interact nonlinearly with mass, supporting the hypothesis of synergistic—or, here, interfering—proprioceptive channels.

Participant feedback corroborated the quantitative data. Users found the task intuitive and reported a rapid learning curve once haptic cues were engaged. Heavier weights helped participants calibrate throwing force but induced mild fatigue over repeated trials—an important methodological limitation, as effort-related drift could confound mid- to late-session throws. Vibrations provided clear release markers but, at higher frequencies (20 Hz), were sometimes perceived as distracting.

Methodological limitations include potential fatigue effects with the 200 g condition, and the question of generalizability beyond discrete throwing gestures. Future work should counterbalance mass order more rigorously or introduce rest breaks to mitigate cumulative fatigue. Extending the paradigm to dynamic targets or locomotion-based tasks would test whether these haptic interactions hold in more naturalistic AR scenarios.

Overall, by merging our inferential results with participant insights, we show that haptic augmentations can both aid and hinder distance perception in AR. Careful tuning of mass and vibration parameters—and deeper comparison to existing perceptual-warping studies—will be essential to translating these findings into practical AR training or gaming applications.

CONCLUSION

We demonstrated that integrating simple haptic augmentation into virtual throwing reduces distance-estimation error in consumer AR by nearly one-third, offering a pragmatic tool for both perception research and immersive interaction design.

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