Unveiling Variations: A Comparative Study of VR Headsets Regarding Eye Tracking Volume, Gaze Accuracy, and Precision

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Abstract

The increasing availability of Head-mounted displays (HMDs) has prompted extensive research to improve gaze interaction in Virtual Reality (VR). Selecting the most suitable HMD for research and design remains a challenge, with gaze accuracy and precision playing crucial roles in determining the efficacy of eye-tracking measurements. This paper compares gaze accuracy, precision, and tracking area across four VR headsets: Tobii Pro, Vive Pro Eye, Vive Focus 3, and Meta Quest Pro (in both stand-alone and tethered modes). All VR headsets exhibit accurate performance in the central region but face challenges in the peripheral area (> 15 degrees), requiring careful consideration for research applications. Variations in sample-to-sample distance and dispersion among headsets impact fixation quality and gaze gestures, influencing the headset choice for specific research needs. Our findings provide valuable insights for researchers and designers, guiding decisions in selecting VR headsets for gaze interaction and enhancing user experiences across diverse applications.

Index Terms: Human-centered computing—Human-Computer-Interaction—Interaction paradigms—Mixed / augmented reality; Human-centered computing—Human-Computer-Interaction—Interaction paradigms—Virtual reality;

1 Introduction and Related Work

Over time, many head-mounted displays (HMDs) have been introduced to the market, aiming to become commonplace gadgets and achieve widespread adoption. The thriving HMD market, projected to exceed 25 billion US dollars by 2030[1], underscores the effort among manufacturers, prompting a wide range in diverse research efforts to enhance interactions in HMDs. Among these interactions, gaze interaction in Virtual Reality (VR) has gained special attention due to its natural and intuitive use [17].

However, as the market keeps expanding, the challenge of selecting the most suitable HMD persists for researchers and designers seeking to maximize the efficacy of their methodologies or applications. Notably, the accuracy and precision of eye tracking significantly influences research quality. While accuracy refers to the degree of conformity between the recorded eye movements and the actual gaze location [4], precision refers to the consistency and repeatability of eye-tracking measurements [4]. Hence, understanding and evaluating the trade-offs, challenges, and capabilities concerning accuracy and precision in VR headset eye tracking is essential for optimizing their functionalities and broadening their applications. While gaze interaction with User Interfaces (UIs) might accommodate slight discrepancies, psychological research requires precise and selective measurement and analysis of gaze. On the other hand, most researchers do not provide the rationale behind their choice of HMD, which could significantly impact their interaction experience and findings or reflect on the headset choice in the collected data.

This paper seeks to analyze a variety of HMDs. By evaluating the capabilities of several VR headsets concerning gaze accuracy, precision, and tracking area, our findings reveal substantial variations among the devices. While accuracy and precision are similar across headsets in the central field of view, they significantly differ in the peripheral region. These results provide valuable insights to assist researchers and designers in making informed decisions when selecting a VR headset for gaze interaction, aligning their choices more effectively with specific research or design requirements. Our research supports further advancements in enhancing user experiences and usability across diverse applications within the evolving landscape of VR technology.

In earlier research, head movements were used as an approximation for gaze interaction. However, recent studies have begun distinguishing between eye and head movements as distinct input modalities [14]. Notably, Llanes-Jurado et al.'s recent work [10] demonstrates that eye tracking outperforms head tracking in accuracy and precision. Still, the study reveals that horizontal head movements closely resemble eye movements, especially in comparison to vertical movements. Furthermore, the authors observe similarities in the behaviour of the eyes and head when dealing with vertical and horizontal object sizes of 25 degrees.

Interestingly, exploring eye-tracking accuracy in HMDs remains somewhat limited. Sipatchin et al. [18] conducted an in-depth evaluation of the Vive Pro Eye, discussing the capabilities and limitations of its eye tracker. Their results expose a latency of $58.1 milliseconds(ms)$, raising concerns about its potential impact on HMD adoption and use cases. Similar results were found by Stein et al. [19] where participants performed 60 saccades between two targets 20° of visual angle apart on three different HMDS, namely, Fove-0, Varjo VR-1, and HTC Vive Pro Eye. The authors found significant delays between headsets ranging from 15 ms to 52 ms, and the latencies ranged from 45 ms to 81 ms, with the Fove-0 being the fastest. Similarly, a recent study by Schuetz and Fiehler compares multiple HTC Vive Pro Eye headsets, focusing on spatial accuracy, precision, and calibration reliability [12]. The findings indicate that accuracy and precision are highest in the central field of view but decrease with greater eccentricity in both axes. A successful calibration is noted across participants, including those wearing contacts or glasses, although glasses yield significantly lower performance. Comparing several Vive Pro Eye headsets, variations in accuracy (but not precision) are identified. Additionally, the study reports accuracy metrics for targets spanning ±15°, revealing a mean accuracy of 1.08° ($IQR: 0.54 - 1.35$), a standard deviation of 0.36° ($IQR: 0.13 - 0.32$), and RMS of 0.2° ($IQR: 0.05 - 0.14$) after correction for outliers.

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[1] https://www.maximizemarketresearch.com/market-report/global-head-mounted-display-hmd-market/28280/

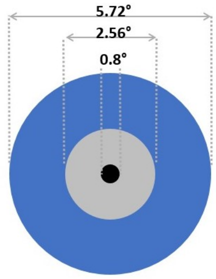

Figure 1: Stimulus during the task: the center black dot (0.8°) is the fixation target.

As new headsets develop, researchers continue to conduct fresh comparisons. For instance, Wei et al. [20] assess tethered PC VR with the Meta Quest Pro with targets spanning a $\pm 15°$ visual field. They reported mean accuracy is 2.162° (*SD* : 0.692), with spatial precision indicated by a mean standard deviation of 0.673 (*SD* : 0.167) and mean RMS of 0.772° (*SD* : 0.461) in the head-restrained condition. These ongoing comparisons contribute to a growing body of knowledge, providing valuable insights into the evolving landscape of eye tracking in VR headsets.

Consequently, in this work, we conduct a comparative analysis of four VR headsets 1) HTC Vive equipped with Tobii Pro eye tracker, 2) HTC Vive Pro Eye, 3) HTC Vive Focus 3, 4) Meta Questo Pro stand-alone, and 5) Meta Questo Pro tethered. Using a simple fixation on targets task, we assess the headsets' capabilities using metrics derived from Holmqvist et al.'s eye tracker evaluation framework [7]: accuracy and precision via standard deviation and RMS, in addition to sampling rate and exploring the 2D volume the integrated eye tracker covers and relate them to the field of view and binocular overlap region.

2 Study Procedure

2.1 Fixation task

After consenting to the experiment, participants were fitted with the HMD and completed the default eye-tracking calibration for the HMD. Participants were then asked to fixate on the target's centre (Fig. 1), which appeared for 2 seconds before teleporting to a new position. Target positions spanned $\pm 25°$ horizontally and vertically on a 7x7 uniform grid. Targets were head-fixed and 1m away from the participants. Participants were asked to keep their heads steady during the experiment. Each participant performed 49 trials per condition $\times$ 5 HMD conditions = 245 trials. The eye-in-head directional vectors and target position-in-headset vectors were collected for analysis. We used a within-subject design, with HMD (eye tracker) being the independent variable. Due to the limited number of participants, the sequence was not fully balanced with a Latin square.

2.2 Eye rotation task

After the fixation task, we asked participants to rotate their eyes and make several circles as large as possible. We use this data later to define the effective 2D volume of the eye tracker.

2.3 Participants

Five participants (age: M = 30.2 years, SD = 4.17; 4 self-identified as male, 1 as female) took part in the experiment. Two wore glasses, and four used VR headsets with eye-tracking daily.

2.4 Aparatus

The TobiiPro, ViveProEye and MetaQuestPro tethered were run on a Windows 11 Lenovo desktop with AMD Threadripper Pro 3955WX Processor and NVIDIA RTX A5000 Graphics. MetaQuestPro, in tethered mode, was connected to the desktop with a Meta Link cable. Applications were built using Unity version 2021.3.24f1. We used the official procedure for all devices to collect the eye-tracking data. We used the Tobii Pro SDK for the TobiiPro HMD, Vive SRanipal for ViveProEye, and Oculus Movement SDK for Meta Quest Pro. For HTC Focus 3, we used the official add-on eye tracker[2], which was only designed to run in stand-alone mode. We used Wave's OpenXR interface to retrieve gaze data.

The eye trackers and Unity running on the HMD application may have different sampling (update) rates. For TobiiPro and ViveProEye, we could save all available gaze data at each Unity frame. For Focus3, and Meta Quest Pro (stand-alone and tethered), only the most recent gaze data was saved at each Unity frame.

3 Data Processing

Participants were required to look at the targets for 2s. For our analysis, we only considered the data of a fixational period. We defined a fixational period as the 1–1.8s since the start of the trial and used the combined gaze in the analysis. As in previous work, we did not use algorithms to detect fixation events due to the influence of the selected thresholds on results [12, 20].

3.1 Preprocessing

During post hoc data processing, we removed invalid gaze samples by calculating the inter-sample gaze velocity and removing those > 800 deg/s [3, 2]. We also removed targets with errors larger than 25°, either due to technical error or participants not looking at the target (possibly being outside their field of view or distracted). Eleven trials were removed (4.5%).

We then transformed gaze 3D directional vectors into 2D Fick angles via the Fick gimbal [6, 8], with Azimuth (Az) representing the horizontal angular rotation of the eyeball, and Polar (Pol), representing the nested vertical rotation. We calculated the spatial accuracy and precision defined by Holmqvist et al. [7] with these angles.

3.2 Accuracy and Precision

Accuracy measures the mean distance in degree between each gaze sample position in the fixation period and the corresponding target position. *Precision* is commonly measured via *standard deviation (SD)* of gaze samples in the fixation period and *root-mean-square (RMS)* of the inter-sample angular distances. SD reflects the spatial dispersion of gaze samples around a mean gaze position and is sensitive to vibration in the environment [7]. In contrast, RMS reflects the sample-to-sample distance and less the dispersion around the mean gaze position [7].

3.3 Processing of different sampling rates

We calculate the eye tracker's sampling frequency (Hz) as f = 1 / inter-sample interval (time between two adjacent samples from the eye tracker) using the gaze timestamps provided by the eye tracker. The Unity frame rate is 1 / the interval in seconds from the last frame to the current one (based on inter-frame timing). The target position is logged in every rendered frame in Unity's Update()-loop[3].

Some APIs provide methods to retrieve gaze data at the eye tracker's sampling rate, which may differ from Unity's frame rate. For the ViveProEye, a dedicated thread collects and logs the gaze data at the eye tracker sampling rate and Unity's most recent target position. For the TobiiPro, the SDK provides a queue to store the gaze samples at the eye tracker sampling rate. We dequeued all gaze samples at every Unity Update() and logged them with the

[2]`https://business.vive.com/uk/product/vive-focus-3-eye-tracker/`, Vive Focus 3 Eye Tracker

[3]`https://docs.unity3d.com/ScriptReference/MonoBehaviour.Update.html`, Unity Update API

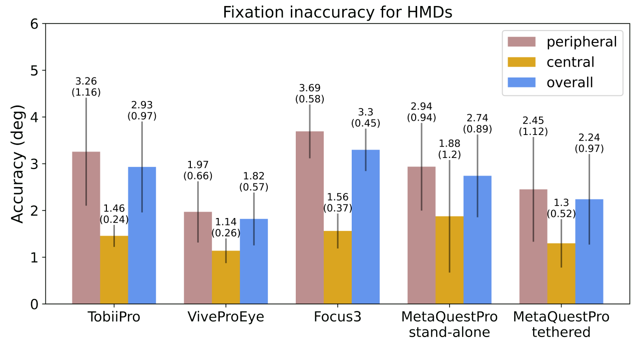

Figure 2: Fixation accuracy for different HMDs, for peripheral (> 15°), central, and overall target positions.

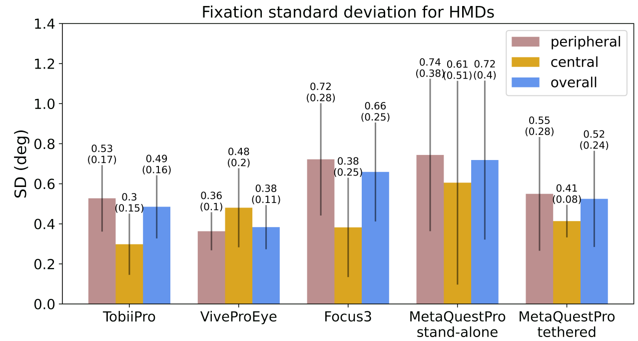

Figure 3: Fixational standard deviation for different HMDs, for peripheral (> 15°), central, and overall target positions.

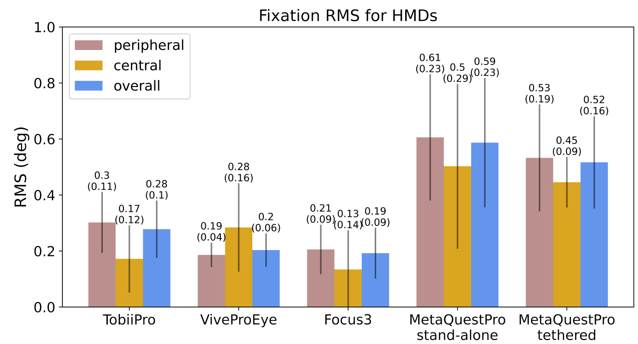

Figure 4: Fixational RMS for different HMDs, for peripheral (> 15°), central, and overall target positions.

most recent target position. Since we could retrieve gaze samples at a higher sampling rate than Unity's Update() frame rate (which is the case for ViveProEye and TobiiPro), there are one or more gaze-target pairs per Unity update. For the other HMDs, we logged the most recent gaze sample exclusively in the Update loop, giving one gaze-target pair every Unity frame. For all HMDs and logging methods, the gaze sample uses the eye tracker timestamp. The target position uses the Unity timestamp. This results in discrepancies regarding the logged data from the eye tracker and Unity. Some samples are lost (or counted twice) for headsets that do not allow native logging of the gaze data in a dedicated thread.

For our analysis of eye tracker accuracy, we require information on the gaze position values from the eye tracker and the target position from Unity. To account for the difference in sampling frequencies between the eye tracker and Unity's refresh rate, we utilized all uniquely timestamped eye tracker samples paired with the closest-matching Unity frame's target position for accuracy and precision calculations.

Unlike fixation metrics, the sampling rate is calculated using all available data, not only from the 800ms-long fixation period.

4 Results

We report the inaccuracy (Fig. 2), standard deviation (Fig. 3), and root-mean-square (Fig. 4) for the fixation period as defined in Sect. 3. For all metrics and targets, the central (< 15°) and peripheral targets are reported, facilitating easy comparison with prior studies that employed targets within ±15° [12,20]. Information on data availability is provided in Appendix A. Results show fixation inaccuracy regarding target locations, with mean deviations not exceeding 3.69°. In the peripheral region, inaccuracies are consistently higher, often doubling those observed in the central area. Further investigation is necessary to understand the differences in fixation accuracy between tethered and untethered modes in devices like the Meta Quest Pro.

Within the central 15° region, mean fixation inaccuracy remains relatively low, typically below 1.88°. Applications using fixation targets with a size of >2° are feasible with these values. This is slightly larger than empirically determined minimum target sizes of 1.5° [13,5] but in line with recommended target sizes of commercially available HMDs (e.g., 2° for Microsoft HoloLens 2 [11]).

The average standard deviations of fixations across the evaluated VR headsets are relatively low (cf. Fig. 3). However, notable differences emerge between tethered and untethered modes in Meta Quest Pro, prompting further investigation into the contributing factors.

Peripheral fixations consistently exhibit higher standard deviations than central fixations across the headsets. Vive Pro Eye and Meta Quest Pro demonstrate relatively stable patterns, while Focus 3 and Tobii Pro show more prominent differences between central and peripheral regions.

The overall root mean square of fixations is low and relatively stable across the VR headsets, with the highest observed at 0.61° for Meta Quest Pro in standalone mode (cf. Fig. 4). Interestingly, this value is twice as high as observed in Tobii Pro, Vive Pro Eye, and Focus 3, all exhibiting RMS below 0.3°. The contrast in Meta Quest Pro's RMS warrants further investigation into the underlying factors contributing to this unexpected variance compared to the other devices.

Fig. 5 shows the eye-tracking sampling frequencies and Unity's update loop frequency per device with the distribution of frequencies. All eye trackers' average sampling rate is close to the manufacturer-reported sampling rate. The Vive Pro Eye's and the Focus 3's distributions show two peaks (111Hz and 125Hz for the Vive Pro Eye and 120Hye and 60Hz for the Focus 3). For the Vive Pro Eye, we believe this to be an artefact of Unity's processing of the eye tracker's callback and the integrated multi-threading. For the Focus3, we believe it is an artefact of recording the data at 90Hz in the update loop of Unity and only accessing the latest eye tracking sample. This leads to an occasional sample loss (it gets overwritten by a new sample during an update loop execution). Note Unity's sampling rate on the Meta Quest Pro is only around 72Hz compared to the higher 90Hz (Focus 3, Vive Pro Eye, and Tobii Pro).

The distribution of fixations per device reveals distinct patterns (Fig. 6), with the ideal scenario being clusters closely aligned around the red crosses representing target locations. Meta Quest Pro and Vive Pro Eye's fixation distribution can be considered good, with samples closely aligning with the red crosses.

Contrastingly, HTC Vive with Tobii Pro exhibits a noticeable drift

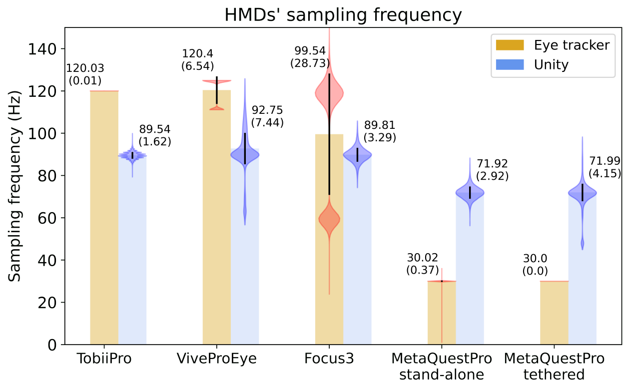

Figure 5: Eye tracker sampling frequency and Unity frame rate for different HMDs. Bar charts represent the mean with standard deviation shown by the black error bars. Violin plots overlay the sampling frequency distribution.

towards the center. Note that this drift appears to be systematic rather than an individual influence from participants. Similarly, Focus 3 displays an overall, seemingly random drift in fixation distribution, once again, without individual participant influence (both tested by inspecting data of the individual participants).

The eye tracking volume is crucial in VR headsets, where more extensive and well-defined boundaries facilitate development and offer more possibilities for interaction and analysis. Fig. 7 illustrates the 2D volumes of the tested devices. In the case of Tobii Pro, the eye tracking volume is large, but the edges are fringy, lacking a precise shape. This points towards a loss of eye-tracking data in boundary regions. On the other hand, the HTC Vive Pro Eye demonstrates a clear, large, and well-defined eye tracking volume. For Focus3, the tracking volume is relatively low in elevation, and a fringy region is at the bottom. Despite this, it is comparable in width to the other headsets. In the case of Meta Quest Pro, the tracking volume is clearly defined, but it exhibits low elevation, similar to the Focus 3, and has a width comparable to other headsets. The overall volume also seems to be shifted slightly downwards in elevation compared to the other headsets.

5 Discussion

5.1 Comparison with previous results

Our results are in the range with previous work regarding central accuracy and precision [18, 12, 20].

In our evaluation, the ViveProEye demonstrates central accuracy for targets within 15° with a mean of 1.14° (SD=0.26), compared to 1.08° (IQR: 0.54-1.35) reported by Schuetz et al. [12]. The overall accuracy is measured at M=1.82° (SD=0.57), as opposed to M=1.8° (SD=0.42) reported by Sipatchin et al. [18]. Similarly, ViveProEye exhibits central precision (SD) with a mean of 0.48°(SD=0.2), compared to 0.36° (IQR: 0.13-0.32) reported by Schuetz et al. [12]. The RMS is measured at M=0.28° (SD=0.16), contrasting with M=0.2°(IQR: 0.05-0.14) reported by Schuetz et al. [12].

For the Meta Pro Eye tethered, our evaluation indicates a central accuracy of M=1.3° (SD=0.52), differing from the reported M=2.162° (SD=0.692) in a study by Wei et al. [20]. Additionally, we measured central precision (SD) as M=0.41° (SD=0.08), in contrast to M=0.673° (SD=0.167) reported by the same study for the Meta Pro Eye tethered. In terms of RMS, our evaluation yielded M=0.45° (SD=0.09), diverging from the reported value of 0.772° (SD=0.461) in the study by Wei et al. [20].

5.2 Spatial Accuracy

All headsets are relatively accurate in the central region, but all struggle in the peripheral region. Research concerned with this area $>15°$ needs to carefully evaluate which headset is the most suitable, as accuracy affects areas of interest (AOI) analysis and interaction.

Our study fixed the targets to the HMD to control their amplitude. In reality, users may turn their heads towards peripheral targets to centre them for better focus and to reduce eye strain caused by large eye rotation [14]. Wei et al. reported a significant increase in the Meta Quest Pro accuracy when head movement is allowed to centre targets [20], while Sipatchin et al. reported a significant decrease in accuracy during head movement phases with the Vive Pro Eye [18]. Together, these results suggest the HMDs can interact with central targets, while peripheral targets may require careful design or utilize error correction modalities [15, 16].

5.3 Spatial Precision via Dispersion and Deviation

The headsets we evaluated exhibited different characteristics of sample-to-sample distance (RMS) and dispersion (SD), which has consequences for research as sample-to-sample distance impacts the quality of fixations. In contrast, dispersion impacts gaze gestures and scan paths. The precision tends to be worse in the periphery for most HMDs, except Vive Pro Eye, with even slightly better precision in the periphery (we believe this to be an artefact of the low sample size as the difference between averages is only 0.01°).

HMDs with higher precision may be more suitable for research where the quality of fixation, saccades, and other gaze metrics are important. The level of precision influences event detection thresholds, and when precision is low, it may fail to detect small saccades [7], prompting careful consideration for the HMD limitations and AOI locations to match the research requirement.

5.4 2D Eye Tracking Volume

The 2D operating volume of the individual eye trackers differs along both axis, elevation, and azimuth (c.f. Fig. 7). All eye trackers generally cover the horizontal binocular overlap region well, some exceeding it. Together with the overall high spatial accuracy and precision, all headsets seem suitable for most applications operating primarily within the binocular overlap region. Our data also suggest that some eye trackers work better in lower elevations than higher ones (e.g. Meta Quest Pro). This is interesting as it coincides with the natural eye-in-head rotation, which is slightly downwards along the elevation axis [9].

Differences in elevation and azimuth coverage might impact headset choice. Applications that require precise data in extreme regions might benefit from headsets that can still record data accurately in very high or low elevations (the same goes for applications based on gaze interactions in the horizontal peripheral field of view).

5.5 Sampling rates

Eye tracker sampling rates, while relatively stable, differ widely between trackers (cf. 5). Surprisingly, newer eye trackers have lower frame rates (at lower application sampling rates). Sometimes, reading eye tracking data using the standard procedure from the manufacturers leads to bimodal distributions, which could, in edge cases (e.g., eye gesture detection based on time series data), lead to increased implementation efforts to circumvent the problem.

Lower sampling rates can generally lead to more errors where dynamic gaze data is required, such as brief events and accurate velocity profiles [7]. For the 30Hz eye trackers such as Meta Quest Pro, saccades would potentially not be recorded reliably, but it may be sufficient for applications that use only fixation positions as input. Appropriate filter, extra- and interpolation techniques (such as the 1-Euro-filter [1]) might be required for these trackers, especially if the application frame rate is higher.

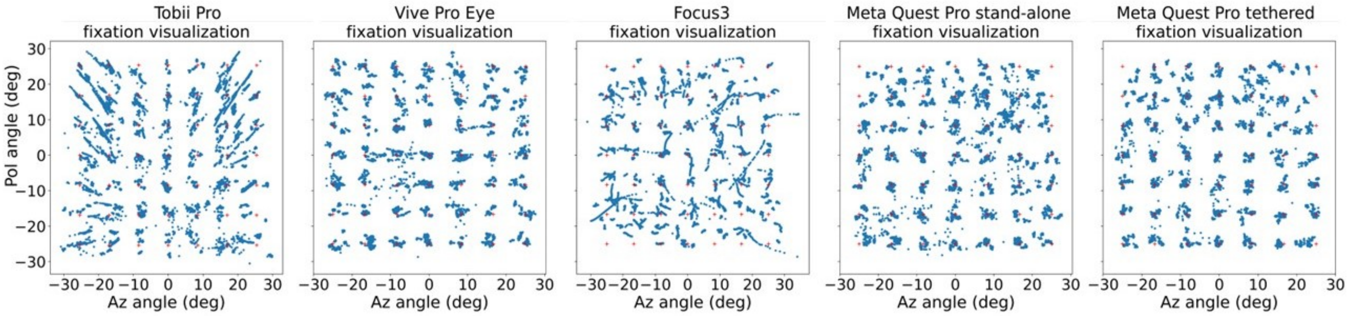

Figure 6: Fixation samples (blue) on targets (red) for different HMDs. Aggregated data of all participants.

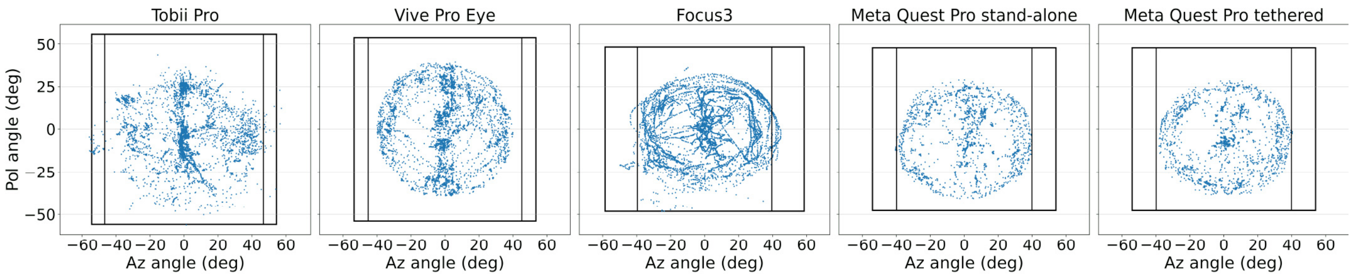

Figure 7: Maximum eye rotation indicated spatial eye tracking limits for different HMDs. Aggregated data of all participants. Rendered fields of view are shown with rectangles, and binocular overlap is shown with vertical lines (data on binocular overlap extracted from `https://vr-compare.com/`).

5.6 Limitations

Limitations of this study include a small participant sample size comprising only five individuals. The analysis also acknowledges that some saccadic movement may persist within the identified fixation periods of 800ms. Further, event detection algorithms were not employed to distinguish fixations, as the outcomes could be influenced by the specific thresholds chosen.

6 Conclusion

In conclusion, our comparative analysis reveals critical considerations for selecting VR headsets in research. While all headsets demonstrate high central accuracy, challenges arise in the peripheral region (>15°), necessitating careful evaluation for relevant research. Variations in sample-to-sample distance and dispersion — precision measures — across headsets potentially impact fixation quality and gaze paths. Additionally, differences in the 2D operating volume along elevation and azimuth axes influence headset choices for applications relying on eye tracking in the periphery. These insights contribute to informed decision-making, guiding researchers and designers in optimizing VR technology for various applications. While we do not claim one headset is better, we believe the outlined data is valuable for practitioners when deciding which headset is perfect for a particular application during the initial project phase.

Acknowledgments

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A Digital Appendix

Raw data, scripts to create graphs and figures, and those used to gather data are available at `https://zenodo.org/doi/10.5281/zenodo.10498170`. Functions for converting between Fick angles, 3D vectors, and visual angles are authored by Per Baekgaard, and available at `https://github.com/baekgaard/fickpy`.

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