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BENCHMARKING THE ACCURACY OF CONSUMER-GRADE CAMERA-BASED HEAD TRACKING SYSTEMS

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Abstract

Deep learning and facial landmarking have enabled the development of consumer-grade camera-based head tracking systems for binaural rendering that do not require specialized hardware. Instead, standard webcams or smartphone cameras provide sufficient input for real-time head pose estimation on desktop or mobile devices. The estimated head orientation is typically transmitted via network protocols, such as Open Sound Control, to drive a binaural renderer. However, precise tracking with low latency is required for high-quality binaural rendering, and it has not been investigated if landmarking-based systems meet these strict requirements. In this study, we benchmarked four such systems against a high-precision reference tracking system with respect to accuracy and latency under static and dynamic tracking conditions, as well as varying illumination conditions and camera setups. Results show that three out of four tested systems reached an accuracy that may be sufficient for many applications, but only one system also achieved a sufficiently low latency.

Keywords: *head tracking, binaural rendering, webcam, latency, accuracy*

1. Introduction

In binaural rendering, instantaneous updates of the simulated acoustic scene to the listener's head orientation through head tracking, commonly referred to as dynamic binaural rendering, can have substantial advantages for source localization [1], externalization [2], and general realism and immersion.
However, the perceptual fidelity of such a system is strongly coupled to the accuracy and latency of the head tracker: angular errors shift the perceived direction of sound sources, while excessive latencies produce an artifact described as "slewing", in which the scene audibly drags behind the head movement [3]. Perceptual thresholds for such latencies range from 60 ms [4] to 100 ms [5] for single sources, and were shown to be about 10 ms higher for a complex sound scene of five sources [6].

The localization blur describes the smallest perceivable angular change in source position, and can serve as a strict criterion for the required tracking accuracy. It depends on the source position and audio content. For sources in the horizontal plane, the localization blur in front of the listener is approximately 1° for speech and 3° for broadband noise. For lateral and rear sources, the localization blur for broadband noise increases to about 10° and 6°, respectively. For sources in the median plane, the localization blur for speech of a familiar person is 9° in front of the listener and increases up to 22° for sources above [7, Sec. 2.1].

High-fidelity optical motion-capture systems such as OptiTrack [8], or electromagnetic solutions such as Polhemus's VIPER [9] or PATRIOT [10] systems, provide sub-degree accuracy and latencies around 10 ms [11], but their cost and calibration demands confine them to dedicated laboratory settings. IMU-based head trackers such as Supperware's Head Tracker 1 [12] have become reasonably affordable and easy to use while achieving comparable accuracy and latency, albeit at the cost of possible drift over time. Camera-based solutions that require only a consumer-grade webcam have become widespread in the gaming and virtual-reality communities. However, comparative evaluations in the context of binaural audio remain sparse.

We therefore benchmarked four consumer-grade software solutions for webcam-based head tracking against an OptiTrack reference in terms of static grid accuracy, dynamic trajectory reproduction, and tracking latency. We tested all trackers with two webcam models of different resolutions, for a total of eight tracker–webcam combinations tested under four illumination conditions.

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2. Methods

To replicate a standard use case scenario of webcam-based head tracking, we conducted our measurements in an office setting. All measurements were performed on the first author, who served as the only subject.

2.1. Technical Setup

An OptiTrack [8] optical motion-capture system with five Flex 13 cameras served as the ground truth, providing a latency of 8.3 ms and a 3D accuracy of ±0.2 mm, according to the manufacturer. OptiTrack's tracking software, Motive, ran on a Windows 11 PC (64 GB RAM, AMD Ryzen 9 5950X CPU, NVIDIA RTX 3080 Ti GPU), tracking a rigid body of four retroreflective markers attached to a pair of beyerdynamic DT 990 Pro headphones worn by the subject. Attaching the markers to headphones also established a realistic scenario for benchmarking the webcam-based systems for binaural rendering, where subjects are often wearing ear or headphones. Orientation quaternions were streamed from Motive via NatNet, bridged to Open Sound Control (OSC), and received by a custom benchmarking software on a Mac mini M4 (16 GB RAM), which also ran the tracking software solutions under test. The Mac mini was connected to two consumer-grade webcams to investigate possible effects of image resolution: a Creative LIVE! Cam Chat HD (720p) and a HiLook HD Webcam (1080p), both at 30 fps. Two instances of each tracking software ran simultaneously, one per webcam, each sending its tracking data via OSC over UDP to the benchmarking software.

2.2. Benchmarking Software

The benchmarking software was written in Python and communicates exclusively via OSC over UDP, making it tracker-agnostic. Each tracker is described by a JSON configuration entry specifying its port, OSC address, data format (quaternion or Euler angles), and nominal update rate. Multiple tracker–webcam instances run in parallel within a single session using multi-threaded OSC receivers, so all trackers are evaluated under identical conditions (illumination and head orientation). All measurement data are stored as CSV and JSON files for offline analysis.

All streams are independently zeroed at session start by recording the current orientation and applying the inverse rotation to all subsequent samples. This software calibration is conceptually separate from the rigid-body pivot reset performed once in Motive. The software supports three measurement modes.

In grid mode, the *static accuracy* of the trackers was tested for a 7×5 grid of target orientations at yaw angles of $\in \{-45, -30, -15, 0, 15, 30, 45\}\,°$, pitch angles of $\in \{-30, -15, 0, 15, 30\}\,°$, and at zero degree roll. The subject was guided to the target orientation through visual aids displayed on the screen and complementary voice guidance played over the headphones. A snapshot measurement was taken after the angular deviation from the target (Euclidean norm of the yaw, pitch, and roll errors) with respect to the OptiTrack reference remained below 3° for 1 s. The tracker error at each grid point is then computed as the difference between the OptiTrack and webcam Euler angles separately for yaw, pitch, and roll.

In trajectory mode, we continuously recorded the tracker angles to test the *dynamic accuracy* for two head movements: a horizontal sweep between yaw angles of −45° and 45°, and a vertical sweep between pitch angles of −30° and 30°, each with 1.5 s per waypoint announced by a voice guide. The trajectories were guided but not strictly controlled; only the starting orientation had to be reached within 3° before the recording started.

In latency mode, the subject performed sharp, impulsive head movements for 10 s, while continuously recording the tracker streams. Both streams were resampled to a common 5 ms time grid, and the supported rotation axes were combined into a single magnitude signal. *Latency* was then estimated as the argmax of the cross-correlation between the reference and tracker signals.

2.3. Trackers Under Test

We evaluated four software head trackers, all of which communicate via OSC and require no hardware beyond a standard webcam. We chose trackers that support macOS and could hence be tested on the same computer, to make the comparison as fair as possible. While there are many other solutions, most of them run exclusively on smartphones or other operating systems. Furthermore, we kept all tracker-specific settings at their default values, except for optional update rates, which we set to their maximum, if available.

HeadTrek `(Version 1.0)` **[13]** is a free, proprietary tracker that transmits orientation as quaternions. The adjustable tracking rate was set to 60 Hz and the smoothing was left at its default value of 100.

FaceOrientation `(Version 1.0.1)` **[14]** is a tracker that outputs yaw and pitch as Euler angles; roll is not estimated. The refresh rate was set to 60 Hz and tilt (i.e., pitch) output was enabled. Its yaw and pitch sign conventions are inverted with respect to the reference and were aligned prior to analysis.

opentrack (neuralnet tracker) `(Version 2024.1.1-matatata.1)` **[15]**, hereafter referred to as *neuralnet*, is the neuralnet input plugin for opentrack, streaming Euler angles. The refresh rate was set to 60 Hz. The default filter "Accela" was used with smoothing set to 1.5° and the deadzone set to the default value of 0.03°.

HeadSite `(Version 1.3)` **[16]** is a tracker that supports the opentrack OSC protocol, outputs Euler angles, and provides no configurable update rate. The *Smooth* slider was left at its default value of 1.0.

2.4. Illumination Conditions

Four complete benchmark sessions were recorded under different illumination conditions, summarized in Table 1. All measurements were conducted on 10 June 2026, in the early afternoon in Berlin, Germany. The room receives daylight through an east-facing window

Table 1: Illumination conditions of the four sessions.

Condition	Ceiling	Ring	Illuminance
Natural	off	off	310 lx
Ceiling	on	off	333 lx
Ring	off	on	628 lx
Ceiling+Ring	on	on	658 lx

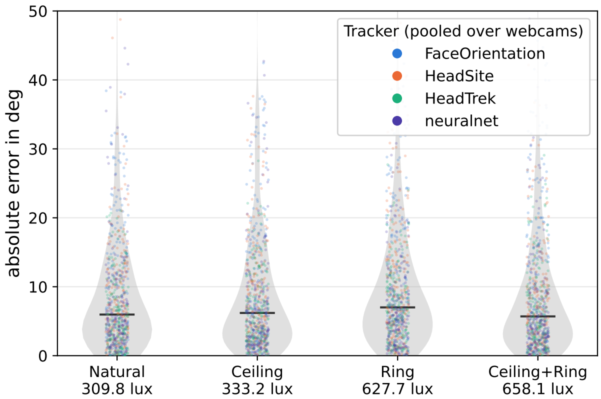

Figure 1: Distribution of the absolute static-accuracy errors per illumination condition, pooled over trackers, webcams, grid positions, and supported rotation axes ($n = 770$ observations per condition, shown as individual points colored by tracker). Horizontal lines mark the medians. The axis is capped at 50°; between 0.3 % and 1.2 % of the observations per condition lie above.

located to the left of the subject. At the time of measurement the sun was in the south-west, so the window contributed only indirect, diffuse daylight. This provided a constant base illuminance of approximately 310 lx (measured with all artificial lights switched off), on top of which a ceiling light and a ring light placed behind the webcams were added, yielding illuminances between 310 lx and 658 lx across the four conditions. Illuminance was measured with a calibrated lux meter placed at head height, facing the webcam.

3. Results

3.1. Effect of Illumination

A repeated-measures ANOVA on the mean absolute error, with illumination condition as the within-unit factor and the eight tracker–webcam combinations as units ($n = 8$), revealed no significant effect ($F(3, 21) = 1.13$, $p = .358$, $\eta^2_G \approx .015$). Grand means differed by at most 1.0° between conditions, and the range across conditions within specific tracker–webcam combinations did not exceed 3.8°, which is below the differences between trackers, whose mean errors spanned 6.1° to 15.1°. This is illustrated in Figure 1: the pooled error distributions are nearly identical across all four illumination conditions, with medians between 5.7° and 7.0°. Moreover, condition-specific errors showed no consistent trend for illuminance: HeadSite with the 1080p camera performed worst under the ring-only condition, whereas the neuralnet tracker with the 720p camera performed worst under the darkest (natural) condition, suggesting residual measurement variability rather than a systematic influence of the tested lighting conditions. All following results are therefore reported averaged over the four illumination conditions.

Table 2: Mean absolute static error, in increasing order, averaged over grid points, supported rotation axes, and the four illumination conditions.

Tracker	Webcam	MAE in °
HeadTrek	1080p	6.1
HeadTrek	720p	6.9
neuralnet	720p	7.4
HeadSite	720p	7.8
neuralnet	1080p	9.2
HeadSite	1080p	10.9
FaceOrientation	720p	14.0
FaceOrientation	1080p	15.1

3.2. Static Accuracy

Figure 2 shows the signed errors of all tracker–webcam combinations per target orientation, and Table 2 summarizes them as mean absolute error (MAE) values. HeadTrek was the most accurate tracker, with MAEs of 6.1° (1080p) and 6.9° (720p), followed by the neuralnet tracker and HeadSite with 7.4° to 10.9°. Notably, the main difference between the three best trackers lay in the roll estimates, where HeadTrek performed much better (720p/1080p MAE: 6.6°/5.3°) than neuralnet (10.5°/16.1°) and HeadSite (8.9°/14.7°). In fact, regarding yaw with the 720p camera, HeadTrek performed even slightly worse (MAE: 8.4°) than neuralnet (MAE: 6.4°) and HeadSite (MAE: 6.8°). FaceOrientation was the least accurate tracker, with MAEs of 14.0° and 15.1°, distributed similarly over its two supported axes (yaw MAE: 12.3°/15.4°, pitch MAE: 15.6°/14.7°). In all cases except FaceOrientation, tracking errors are smaller for close to neutral head orientations (see numbers in parentheses given in Figure 2). The higher-resolution camera did not systematically improve accuracy: only HeadTrek benefited slightly from the 1080p camera, while all other trackers performed better with the 720p camera.

Two error patterns are apparent in Figure 2. First, errors generally grow as the absolute yaw angle increases toward the extremes of the tested range (±45°), where the face is seen at an oblique angle, an effect that becomes even more pronounced at large pitch angles (up to ±30°). This particularly affects the roll estimates of HeadSite and the neuralnet tracker, especially with the 1080p camera. These trackers exhibit pronounced yaw-to-roll cross-talk: they report a spurious roll component that grows with the absolute yaw angle, even though no roll was present. Second, FaceOrientation's errors are particularly large, and the underlying clipping and quantization behavior is clearly visible in the trajectory measurements discussed in the following section.

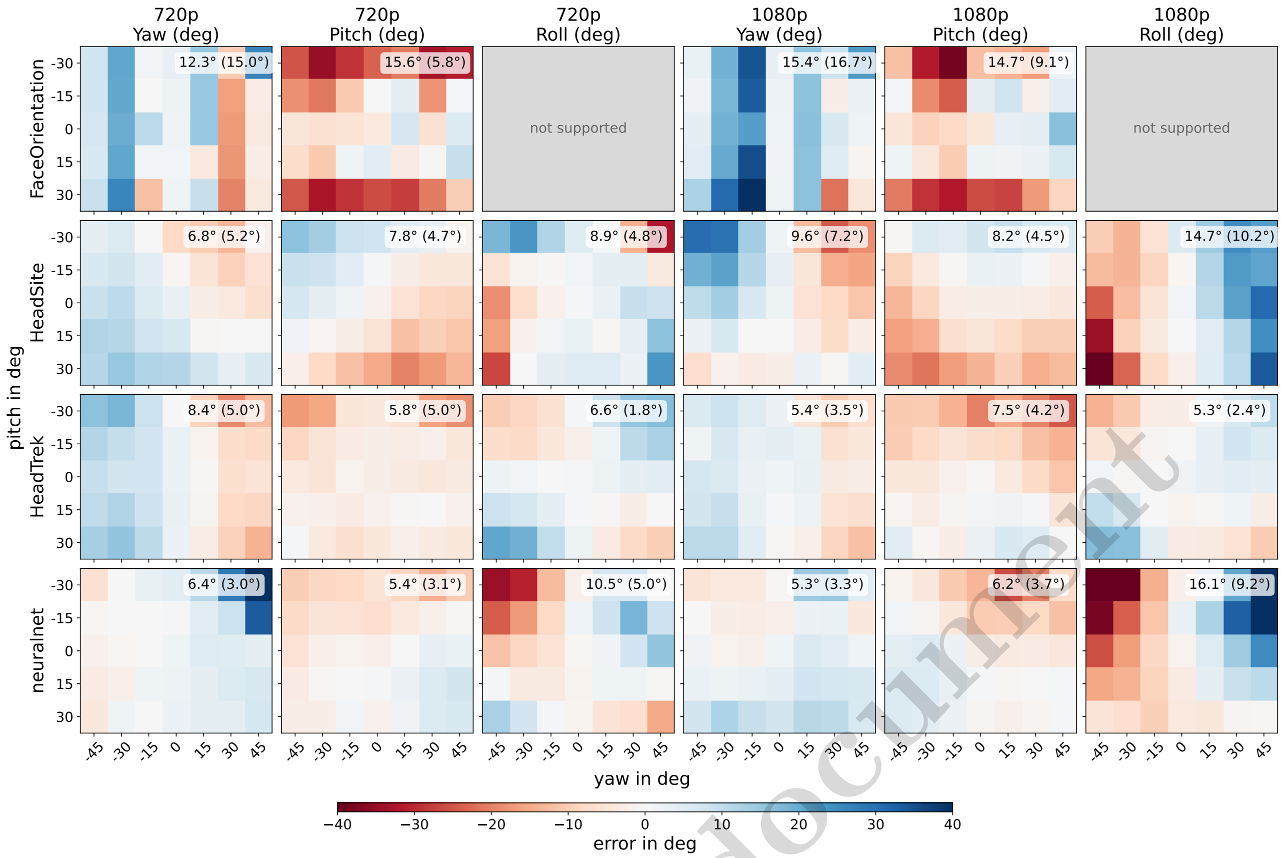

Figure 2: Signed errors of the static accuracy test (OptiTrack minus webcam tracker) per target orientation, averaged over the four illumination conditions. Rows show the trackers, columns the webcam–axis combinations. The text label in the top right of each panel gives the MAE over the full grid and, in parentheses, the MAE over the central range (±30° yaw at 0° pitch).

3.3. Dynamic Accuracy

Figure 3 shows the recorded trajectories of the horizontal and vertical sweeps for the ceiling+ring illumination. HeadTrek follows the reference closely on all three axes with both cameras, without visible crosstalk. The neuralnet tracker and HeadSite reproduce the yaw and pitch sweeps well, but show increasing spurious roll with increasing yaw during the horizontal sweep, reaching up to about 30° at the maximum tested yaw angles with the 1080p camera. FaceOrientation exhibits two additional artifacts. First, its yaw output clips at approximately −50° and progresses in coarse, staircase-like steps. Second, its pitch output only loosely follows the vertical sweep.

3.4. Latency

Table 3 lists the estimated latencies relative to the OptiTrack reference, whose own motion-to-output latency is below 10 ms [11]. HeadTrek with the 720p camera was by far the fastest combination at 40 ms. All other combinations exceeded 100 ms, with FaceOrientation approaching 400 ms. Notably, the higher-resolution camera increased latency consistently for every tracker, by 53 ms to 95 ms, presumably due to the increased image-processing load. Together with the accuracy results above, this indicates that a higher camera resolution was not beneficial for any of the trackers under test.

Table 3: Latency relative to the OptiTrack reference, in increasing order, estimated from the combined-axis cross-correlation and averaged over the four illumination conditions.

Tracker	Webcam	Latency in ms
HeadTrek	720p	40
HeadTrek	1080p	104
HeadSite	720p	164
neuralnet	720p	188
HeadSite	1080p	246
neuralnet	1080p	283
FaceOrientation	720p	345
FaceOrientation	1080p	398

4. Discussion

Referring to the perceptual criteria outlined in Section 1, only one of the eight combinations meets the latency requirements for dynamic binaural rendering: HeadTrek with the 720p camera (40 ms) stays below even the strictest reported threshold of 60 ms

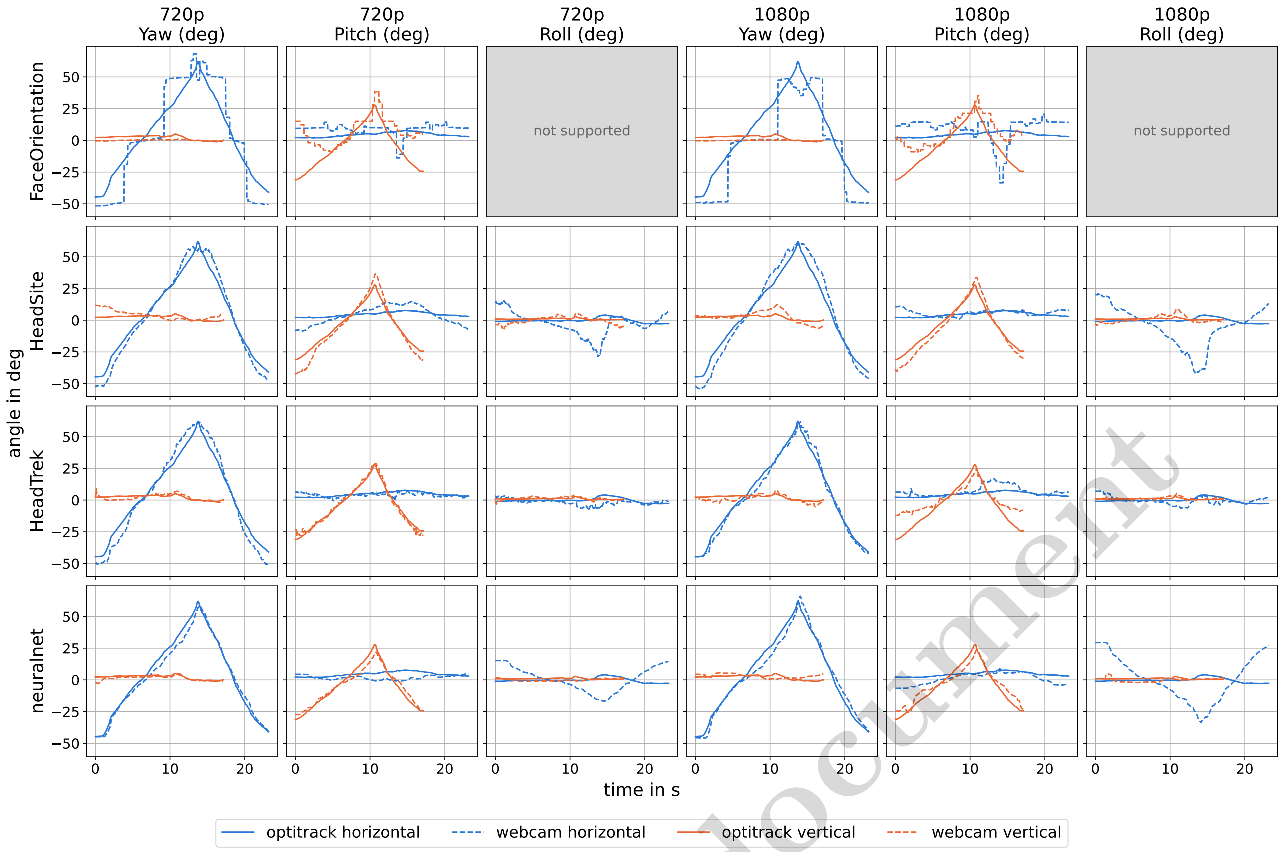

Figure 3: Horizontal (yaw) and vertical (pitch) sweeps recorded in the brightest illumination condition (ceiling + ring light, 658 lx). Rows show the trackers, columns the webcam–axis combinations. Solid lines: OptiTrack reference; dashed lines: webcam tracker. Blue: horizontal sweep; orange: vertical sweep. Gray panels mark axes not estimated by the respective tracker.

[4]. HeadTrek with the 1080p camera (104 ms) is borderline with respect to the more lenient 100 ms threshold [5], while all remaining combinations exceed even that by a factor of 1.6 to 4.0 and can be expected to produce audible slewing. It should be noted that we did not consider audio-processing latency. For 64 to 512 sample input and output buffers used in a real-time audio processing pipeline, additional latencies between 2.7 and 21 ms would be added at a sampling rate of 48 kHz, not including converter latency, safety buffers, or additional plugin delay.

The static accuracy test showed that the MAEs for yaw exceed the localization blur. For close to neutral head orientations (yaw angles within ±30°, pitch 0°) and the 720p webcam, we found MAEs between 3° (neuralnet) and 5° (HeadTrek, HeadSite) for the three best performing trackers, compared to a localization blur of 1° for a frontal speech source. For head orientations over the entire tested range and the 720p webcam, MAEs increase to around 6° to 8° for the three best performing trackers. Taking into account that the localization blur (i) is measured under noise-free anechoic conditions for a single sound source, (ii) is larger for non-speech sounds (e.g., 3° for noise), and (iii) increases to 10° for lateral sources, the observed accuracy may be sufficient for many applications. For pitch, we observed MAEs between about 5° and 8° for the three best performing trackers and the 720p webcam, which is below even the smallest localization blur of 9° for a frontal, familiar speech source.

The pronounced yaw-to-roll cross-talk of HeadSite and neuralnet is more problematic because spurious roll of up to 30° would cause a potentially audible tilt of the entire sound scene during natural head rotations. However, we maintained roll angles of 0° for all tested head orientations, which does not reflect natural human head motion. For example, humans typically roll their heads during yaw rotations: rotating the head to either side by about 70° is accompanied by roughly 25° of coupled roll on average, i.e., about a third of the yaw angle [17, Table 1]. One possible explanation is that the models used for HeadSite and neuralnet may have been trained predominantly on image data from photographic and video recordings of people performing natural head movements. The models may never have encountered large yaw angles with zero roll during training. This could cause the models to predict an expected amount of roll for a given yaw angle.

The illumination conditions had a negligible effect on

tracking accuracy. This is encouraging for practical use, but two caveats apply: the darkest condition still provided 310 lx of diffuse daylight, so performance in genuinely dim environments remains untested, and the effect on latency was not analyzed separately.
Some limitations of this study should be noted. All measurements were performed with a single male subject with light skin tone, and hence results might not completely generalize to other subjects. Each illumination condition was measured once, so within-condition variability could not be assessed. The two webcams differed not only in resolution but also in manufacturer and hardware, so the observed differences cannot be attributed to resolution alone. The trackers were used with their default smoothing settings, which likely contributed to the measured latencies. Furthermore, a generalizable statement about the influence of illumination would require measurements in a light-tight studio, covering a wider range of illuminance levels and including direct light sources. In this sense, the scope of our results is limited to the tested scenarios. Finally, since the head movements were guided but performed freely, the trajectory measurements do not characterize strictly repeatable motion.

5. Conclusion

We benchmarked four consumer-grade, webcam-based head-tracking solutions against an OptiTrack reference in terms of static accuracy, dynamic trajectory reproduction, and latency, using two webcams and four illumination conditions. Within the tested range of 310 lx to 658 lx, illumination had a negligible effect, whereas the choice of tracker and camera dominated the results: static MAEs ranged from 6.1° to 15.1° and latencies from 40 ms to 398 ms. The higher-resolution camera consistently increased latency without systematically improving accuracy. Only HeadTrek combined with the 720p camera met established perceptual latency thresholds for dynamic binaural rendering, while also showing the smallest overall MAEs and no recognizable yaw-to-roll cross-talk, an artifact that led HeadSite and the neuralnet tracker to report spurious roll of up to 30° at large yaw angles.

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