Eye Tracking Performance in Mobile Mixed Reality

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Abstract
Implementing and evaluating eye tracking across multiple platforms and use cases can be challenging due to the lack of standardized metrics and measurements. Additionally, existing calibration methods and accuracy measurements often do not account for the common scenarios of walking and scanning in mobile AR settings. We conducted user studies evaluating eye tracking on the Magic Leap One, the Meta Quest Pro, and the HoloLens 2. Our results reveal that the degree to which locomotion influenced eye tracking performance depended on the headset, with the HoloLens 2, which features a retractable visor, displaying the greatest decrease in accuracy during locomotion.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies; Human-centered computing—Ubiquitous and mobile computing—Ubiquitous and mobile devices—Mobile devices;

1 Introduction
Recent advancements in eye-tracking technology have made it more accessible and affordable for a wider range of applications [3]. As such, it is important that developers and users understand the capabilities and limitations of their eye tracking devices during use. With the rise of head-worn augmented reality (AR) displays such as the HoloLens 2, Magic Leap, Meta Quest Pro, and the Apple Vision Pro, eye trackers have been integrated into various platforms and use cases. However, optimally utilizing eye-tracking technology on multiple platforms and standardizing their performance is a difficult and complex problem.

Specific metrics, such as accuracy and precision, are often used to evaluate the performance of eye tracking systems [1, 3, 4]. Although existing work has used these metrics to examine the accuracy of eye trackers while stationary, there has been little research into how locomotion affects eye tracking, even though there is considerable interest in mobile eye tracking for specific applications, such as assessing behaviors for shopping, navigation, or wayfinding [2, 5]. Current calibration methods for eye tracking devices rely on users keeping their heads stationary, without incorporating any head or body movement. It is unclear whether these methods are effective when a user intends to use eye tracking while walking.

Our objective is to establish improved testing practices for mobile eye tracking development in AR headsets, particularly during locomotion. To achieve this goal, we conducted three user studies to assess the spatial accuracy and precision of the gaze signal captured by the integrated eye tracker of the Magic Leap, Meta Quest Pro, and HoloLens 2. We present the results of our study and provide an analysis of the eye tracking signal quality, focusing on accuracy across various AR scenarios.

The insights gained from this study contribute to our understanding of the variations in eye tracking accuracy observed across different tasks in our test suite, which can be attributed to the hardware design of the respective headsets. Both datasets will be made publicly available for further research and analysis.

2 User Studies
Three separate user studies were carried out to evaluate the performance of eye tracking on different devices: the Magic Leap 1 \( n = 36 \), the Meta Quest Pro \( n = 29 \), and the HoloLens 2 \( n = 54 \), with slight modifications to adapt the test suite to differences in the three headsets. We outline the tasks presented in the three studies below.

Head-Constrained Static (HCS) Users rest their head on a chin rest and watch a tracking stimulus on the screen, which shifts to random positions after a brief delay.

Head-constrained Moving (HCM) Users rest their head on a chin rest and watch a tracking stimulus, which moves along a path on the screen inside their field of view (FOV).

Body-constrained (BC) Users sit and turn their head to watch a tracking stimulus, which moves along a path in the world frame of reference (FOR) and wider than their FOV.

Screen-Stabilized Walking (SSW) Users walk in circles around a table while watching a tracking stimulus, which moves along a path on the screen inside their FOV.

World-Stabilized Walking (WSW) Users walk in circles around a table while watching a tracking stimulus, which moves along a path in the world FOR above the table.

In addition to these five common tasks, only the user study performed on the HoloLens 2 incorporated one additional unique task, the hallway task. This task was added due to participant feedback that the existing tasks, which incorporated walking in circles around a table, felt unnatural and unintuitive. Our goal was to create a walking task that might more closely resemble real-life use-cases of augmented reality with locomotion.
ONCLUSION AND
J. de Winter, P. Bazilinskyy, D. Wesdorp, V. de Vlam, B. Hopmans,
Eye tracking methodology: Theory and practice
P. Kiefer, I. Giannopoulos, M. Raubal, and A. Duchowski. Eye tracking

= RESULTS

Users walk down a hallway while watching a tracking
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Hallway (H) Users walk down a hallway while watching a tracking
stumbling, which moves down the hallway in front of them.

3 Results

Results for all three studies are summarized here. Exactly like [1],
we employed the inverse cosine of the dot product between the gaze
and stimulus vectors to establish the cosine error.

Fig. 2 shows a graph of cosine error split by task for all three
devices. Due to the different numbers of participants in each user
study, the data from 29 random participants was selected from the
Magic Leap One and HoloLens 2 studies in order to match the
quantity of data available from the Meta Quest Pro and allow for
a better comparison of the three studies. An ART ANOVA with
independent variables “task” and “device” revealed a significant
difference in cosine error between tasks ($F = 341.1, p < 2.22 \times 10^{-16}$),
a significant difference in cosine error between devices ($F = 49.9, p < 8.77 \times 10^{-15}$), and an interaction between task and device ($F = 147.8, p < 2.22 \times 10^{-16}$). For the Magic Leap One and Meta Quest
Pro, a Bonferroni-corrected Mann-Whitney U posthoc test reveals a
difference in cosine error in the world-stabilized walking task ($p = 0.0024$). For the Magic Leap One and HoloLens 2, the same posthoc
test reveals a difference in cosine error in the head-constrained static
task ($p = 1.94 \times 10^{-6}$), the body-constrained task ($p = 1.01 \times 10^{-6}$),
the screen-stabilized walking task ($p = 1.32 \times 10^{-7}$), and the world-
stabilized walking task ($p = 4.02 \times 10^{-10}$). For the Meta Quest
Pro and HoloLens 2, the posthoc test reveals a difference in cosine error in
the same tasks: the head-constrained static task ($p = 7.5 \times 10^{-5}$),
the body-constrained task ($p = 3.6 \times 0^{-5}$), the screen-stabilized
walking task ($p = 6.48 \times 10^{-8}$), and the world-stabilized walking
task ($p = 2.4 \times 10^{-10}$).

Our overall results for the HoloLens 2 indicate that spatial accuracy
for the hallway task is lower than the error on either walking
task, but higher than the error on non-walking tasks.

4 Discussion

Overall, the HoloLens 2 results differed the most from those of the
other two headsets, with significantly higher errors, especially in
walking tasks. This may be due to the difference in display quality
which sometimes made the tracking stimulus difficult to see during
the task. Although the hallway task was more accurate than either
of the other two walking tasks, it was still less accurate than any of
the tasks without locomotion.

The only task for which the Meta Quest Pro and Magic Leap
have significantly differing eye tracking performance is the world-
stabilized walking task, in which the Meta Quest Pro has a lower
accuracy than the Magic Leap One. This may be due to the Meta
Quest Pro using a video pass-through display instead of an optical-
see-through display. Seeing the world through an imperfect video
feed while navigating around a center table that is to be kept in focus
is more taxing to the human visual system than using an optical-see-
through display.

The differences between the accuracy of the HoloLens 2 com-
pared to the Magic Leap One and Meta Quest Pro may largely be
explained by the fit of these headsets. The Magic Leap One rests on
the nose, forming a secure fit around a user’s eyes, and is the only
headset having its compute unit separated from the headset, making
it relatively stable while moving. The Meta Quest Pro uses a band
that wraps around the forehead, with the display fixed in place. In
contrast, the HoloLens 2 has a visor housing the display that can be
flipped up, which can result in a lack of stability between the display
and the eyes. This leads to more possibility of headset movement
and thus, lower accuracy for tasks when head and body motion in-
crease. The lack of a stable fit of the HoloLens 2 may contribute to
its significantly lower accuracy of the eye tracker unless the head is
kept still, whereas the Magic Leap One and Meta Quest Pro headsets
show more consistent eye tracking accuracy throughout.

In fact, for the head-constrained static task, the HoloLens 2
exhibited better eye tracking performance than the Magic Leap and
Meta Quest Pro. This can be due to the greater distance between
the display and the user’s eyes on the HoloLens 2, which may have
allowed its eye tracking cameras to better capture eye gazes at the
periphery of the display. Differences in the built-in calibration
procedure may also have an effect here.

5 Conclusion and Future Work

In this work, we compare the eye tracking capabilities of the Magic
Leap One, Meta Quest Pro, and HoloLens 2 during locomotion. The
included tasks account for when a user is sitting with their head
held still, sitting with their head freely moving, or walking, as well
as whether a user is viewing screen-stabilized, body-stabilized, or
world-stabilized content.

Overall, our work provides future researchers with a means of
investigating the accuracy of the eye tracker of their AR device.
This may allow researchers to gain valuable insights, improving the
performance of their eye tracker in mobile mixed reality applications.

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