SPECIAL SECTION PAPER

WILEY

Differences between oculomotor and perceptual artifacts for temporally limited head mounted displays

Alexander Goettker, SID Member[1,2] | **Kevin J. MacKenzie, SID Member**[1] |
T. Scott Murdison, SID Member[1] ⓘ

[1]Facebook, Redmond, Washington, USA

[2]Justus Liebig University Giessen, Giessen, Germany

Correspondence
T. Scott Murdison, Facebook, Redmond, WA, USA.
Email: smurdison@fb.com

Abstract

We used perceptual and oculomotor measures to understand the negative impacts of low (phantom array) and high (motion blur) duty cycles with a high-speed, AR-likehead-mounted display prototype. We observed large inter-subject variability for the detection of phantom array artifacts but a highly consistent and systematic effect on saccadic eye movement targeting during low duty cycle presentations. This adverse effect on saccade endpoints was also related to an increased error rate in a perceptual discrimination task, showing a direct effect of display duty cycle on the perceptual quality. For high duty cycles, the probability of detecting motion blur increased during head movements, and this effect was elevated at lower refresh rates. We did not find an impact of the temporal display characteristics on compensatory eye movements during head motion (e.g., VOR). Together, our results allow us to quantify the tradeoff of different negative spatiotemporal impacts of user movements and make subsequent recommendations for optimized temporal HMD parameters.

KEYWORDS

eye movements, motion blur, phantom array, temporal light artifacts, head-mounted displays, virtual and augmented reality

1 | INTRODUCTION

A naturally illuminated scene emits a continuous stream of light to our eyes (e.g., Figure 1, top row). In contrast, a reproduction of that same scene on a display emits discontinuous periods of light presented at some frequency (typically defined as display refresh rate) and illuminated for some time (typically defined in absolute units of persistence [msec] or frame-proportional units of duty cycle [%]). Though intended to give the impression of continuity, this temporally limited presentation of light to the user can violate the expectations of the perceptual system and result in perceptual artifacts, depending on the violations. For example, overall low refresh rate can result in perceived flicker. For example, in early motion picture technology, 24 fps frames would be shuttered three times leading to an effective frame presentation frequency of 72 Hz—eliminating visible flicker for most viewers. Pixel persistence properties can lead to blur due to smear, or motion, as well as issues like judder. This is especially challenging for HMDs due to the display requirements needed to account for motion from head and eye-in-
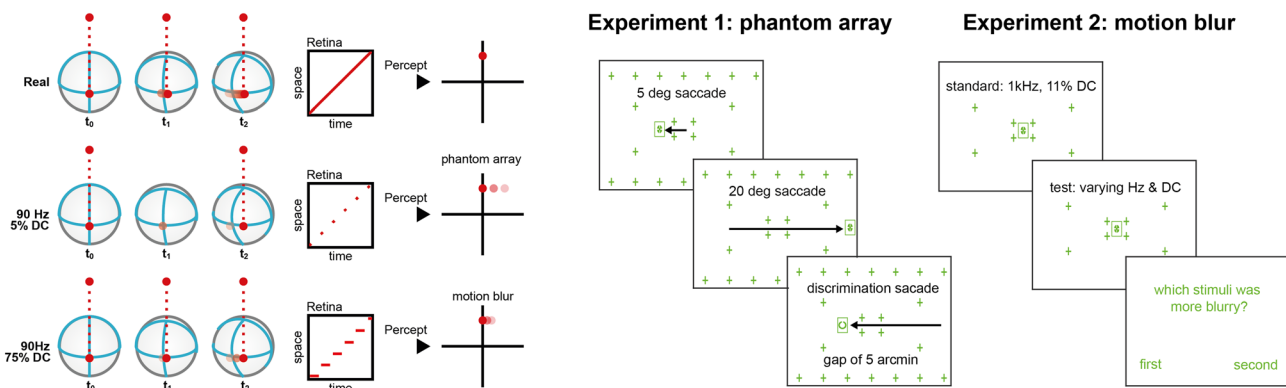
FIGURE 1 Illustration of the phantom array and motion blur artifact during eye movements for displays with different duty cycles (middle and bottom). The real world input comparison depicted at the top. Schematic depiction of the two experiments to investigate the impact of both artifacts. Note that the size of the symbols does not depict the real size during the experiments. For detailed information about the paradigms the reader is referred to the method section

headmovement—resulting in various spatiotemporal artifacts for virtual objects.

Displays with limited refresh rate in combination with longer duty cycles (high persistence) can induce the strong percept of motion blur.[1] This is especially prominent during smooth rotations of the eye such as pursuit (when following a moving object with the eye) or under the vestibulo-ocular reflex (when counter-rotating the eyes during head movements to maintain stable fixation). During the vestibulo-ocular reflex (VOR), the image on the HMD has to be continually updated to appear stable in space. However, the limited temporal sampling leads to long presentations of a static image, where each illuminated pixel is smeared across different receptors on the retina during the rotation of the eyes (see bottom row of Figure 1). This smearing results in a blurry object percept that can impact dynamic visual acuity.[2]

To eliminate visible motion blur during head motion, HMDs typically operate under short duty cycles (e.g., less than ~10% of the frame time). However, as shown by previous literature,[3,4] short duty cycles during saccadic eye movements—fast movements to direct the gaze to relevant objects in the visual field—can introduce a perceptual artifact often referred to as phantom array or strobing. Phantom arrays manifest as several illusory copies of the displayed content across the visual field.[3,4] These presumably occur because the sparse, high spatial frequency, input of the display is spread out across the retina through discrete time intervals during saccades.[5] The spread of the relevant information across the retina then cannot be integrated into a continuous percept (see Figure 1 middle row).

Although the temporally limited nature of HMDs is problematic for the visual experience, these limitations might also be problematic for saccadic eye movement control, whose primary function is to bring targets of interest from the retinal periphery into the high acuity fovea.[6,7] For motion blur during VOR, the oculomotor problem is obvious: if the retinal image blurs with head movements, in addition to seeing a blurry image, the user may have trouble maintaining fixation on a virtual object in the world due to the induced retinal motion from persistence-driven blur (driving eye movements in the direction opposite the VOR movement). Thus, any oculomotor effects due to this additional retinal blur would be apparent in the measured VOR gain, the ratio of eye, and head velocity during movement.

The potential oculomotor problems associated with phantom array are less obvious, as pre-, trans-, and post-saccadic visual processing is less understood and an area of active research. However, there are multiple potential mechanisms that are relevant for saccade control that could be affected by the temporally limited nature of the visual input. During target selection, less clearly defined targets, for example, due to low contrast[8,9] or increased spatial uncertainty,[10] are related to less accurate saccades. Also, remapping mechanisms,[11–14] which are thought to be involved in our impression of perceptual continuity during saccades, rely on spatially and temporally accurate estimates of the eye's current and future positions relative to the incoming visual input. Although saccades are classically thought to be ballistic, even during flight, online adjustments of saccades are possible due to changes in retinal target position in flight.[15] By effectively adding multiple target positions to the retinal projection, phantom arrays might trigger such a correction mechanism.

Less accurate or otherwise altered oculomotor targeting may have negative consequences on a user's ability to resolve fine details of displayed information due to an unpredicted and potentially more eccentric position

of the target on the retina. Such increased eye movement errors might require additional corrective movements, which could lead to longer visual processing times for otherwise simple visuomotor tasks, such as reading. To our knowledge, it is currently unknown whether the temporal limitations of HMDs impact eye movement control.

The choice of optimal temporal HMD properties therefore presents a natural optimization problem: What refresh rate and duty cycle minimize both perceptual and any potential visuomotor impacts of motion blur and phantom arrays? Although there is already some research on the perceptibility of each of the individual artifacts,[1-4] there is currently no systematic investigation of the tradeoff between the two as a function of temporal display properties. Thus, understanding how these properties influence the appearance of motion blur and phantom array and if, by extension, these spatiotemporal artifacts influence eye movement control is an important step for virtual (VR) and augmented reality (AR) HMD development.

2 | METHODS

We conducted two experiments to study the effect of HMD refresh rate and duty cycle on perceived eye movement-induced phantom arrays and head movement-induced motion blur, respectively. The first experiment quantified both the detectability of phantom array artifacts and any changes to saccadic eye movement behavior. Under the same temporal display conditions as experiment one, the second experiment quantified the perception of motion blur during natural head movements. Together, these two experiments allowed us to systematically evaluate the perceptual and visuomotor tradeoffs of temporal HMD properties during typical user eye and head movements.

2.1 | Apparatus

We constructed a high-speed (max refresh rate ~9 kHz), digital micromirror digital light-projection display (DMD, DLP9000X from Texas Instruments) with 50/50 see-through binocular viewing optics (two STAR CORE systems from Vialux, with custom machined fittings), which produces monochrome, binary images from an LED light source (CBT-90 green LED from Luminous with peak at 532 nm and bandwidth of 530–535 nm). Because traditional DLP displays present different image greyscales sequentially using subframes, we avoided confounding contouring artifacts due to eye movements during this presentation scheme by limiting our visual stimuli to 1-bit luminance, similar to other persistence investigations using DLP-DMD displays.[2] Therefore, we used a single subframe per stimulus presentation. Additionally, eliminating higher-bit subframes had the added benefit of providing greater temporal resolution (i.e., higher refresh rates and lower duty cycles) for our display system. This setup allowed us to simulate an additive AR display, with a wide range of possible refresh rates and duty cycles. The pixel pitch of the display was 2.5 arcmin (through a polymer-on-glass diffusor layer from RPC with a grain size ~1 μm), and we used 1,024 * 576 pixel images. The resulting field of view of the display was 43 * 25 deg of visual angle and had a focal plane of 0.5 D (2 m). The display was attached to a 1 deg of freedom rotational stage with a high-resolution quadrature angular encoder (from US Digital with 25,000 counts-per-revolution, giving ~0.9 arcmin steps). We used this during experiment 2 to track the current position of the head in the apparatus and feed the signal back to the display rendering pipeline for the presentation of stimuli that appear fixed in the world. In addition, eye tracking with a 500-Hz sampling frequency was provided by Eyelink II (from SR Research) cameras. In order to maintain a constant eye-camera relative position, we used an individualized bite bar with quick-setting dental putty. When looking through the display, participants faced a projection screen, which was independently illuminated by a VPixx ProPixx projector (from VPixx Technologies) mounted above the display.

In order to compare the results across experiments the simulated display properties were the same for both experiments. We varied the refresh rate in three steps (90, 180, or 240 Hz) and the duty cycle of the display in eight steps (5%, 10%, 15%, 20%, 40%, 60%, 65%, and 75%). Note that despite constant duty cycles across the different refresh rates, because the duty cycle is a proportion of frame duration given a certain refresh rate (~11.1 ms for 90 Hz, ~5.6 ms for 180 Hz, and ~4.2 ms for 240 Hz), the time the display was illuminated per frame (the persistence) did vary across refresh rates. Stimuli with higher duty cycle emitted more light and are therefore perceived as brighter and easier to detect. We controlled for this by measuring the brightness of the stimuli with a Konica Minolta CS-160 luminance meter (Konica Minolta Sensing Americas, Inc.) and produced a constant 10:1 contrast for all different conditions by adjusting the background brightness accordingly.

2.2 | Procedure

We recruited a total of 25 participants for the two experiments (six identifying as female, 19 identifying as male, ages 21–44). Fourteen took part in experiment 1 and 16 took part in experiment 2. Each had normal or

corrected-to-normal visual acuity and reported no known neurological disorders. Participants were briefed and shown demos with the kind of artifacts to expect at the beginning of the respective experiment and performed practice trials to get used to the task.

Experiment 1. The task in experiment 1 was to look a target cross (1 deg in diameter[16]) at varying positions on the screen. After the cross appeared at two position a Landolt C (gap of 5 arcmin randomly in one of the four cardinal directions, diameter 25 arcmin) appeared at a third position and participants had to judge the orientation of the gap. At the end of each trial, participants reported whether they perceived the phantom array artifact at any moment during the trial. To increase the sensitivity for seeing the phantom array artifact, in addition to the targets we added square frames around the target (2 deg wide with single-pixel edge widths) and otherwise-irrelevant crosses throughout the visual field (see Figure 1, middle panel).

At the beginning of each trial, participants saw a central target and started the trial via button press. The first target appeared either 5 deg to the left or the right of the initial central fixation cross. The target stayed visible for a random time between 750 and 1500 ms and then stepped 20 deg into the opposite direction. It remained visible for a different random duration between 750 and 1500 ms. Afterwards, the discrimination target appeared at random horizontal position in a distance between 21 and 25 deg. We randomized this position to guard against memory-evoked, and not-visually-evoked, saccades. We constrained the presentation time of the target to 50 ms after the gaze had crossed the midline of the screen and displayed a random noise mask immediately afterwards to eliminate the potential effect of retinal afterimages. The mask disappeared after 300 ms and participants had to indicate the orientation of the gap by pressing one of the four arrow keys. Due to the small gap size and time constraints, the discrimination task was sensitive to any changes in oculomotor behavior.

One block consisted of 72 trials (3 refresh rates * 8 duty cycles * 3 repetitions per combination). In each block, we additionally added 10 random trials, where we presented five trials with 90 Hz and 5% duty cycle and five trials with 240 Hz and 75% duty cycle but used a background brightness that was randomly modulated by a factor of 2 or 5 either up for 5% duty cycle or down for 75% duty cycle. These trials where not part of the analysis and were only added in an attempt to decorrelate brightness and duty cycle to force participants to not base their judgments on the brightness of the background. One block lasted roughly 15 min and participants completed between 3 and 10 blocks.

Experiment 2. The task in experiment 2 was to perform head movements while fixating a central target and compare which of two sequentially presented stimuli was blurrier. We used comparable stimuli as in experiment 1 (see Figure 1, right panel); however, this time the target always stayed world-locked and in the center of the image. In one trial, participants saw both stimuli for 3 s each. During the 3 s, participants were instructed to move their head roughly 30 deg to one side, then to the respective other side, and back to the center. Auditory signals indicated the start and end of the interval, allowing participants to maintain a consistent velocity profile through self-pacing. One of the two stimuli was always a standard stimulus (11% duty cycle, 1000 Hz refresh rate), which led to the percept of no motion blur. The second stimulus was the test stimulus which varied with the same pairs of refresh rate and duty cycle as the stimuli in experiment 1. The test-standard interval order was randomly varied from trial to trial. After seeing both trials, participants indicated via key press which of the stimulus appeared blurrier and afterwards continued with the next trial. One block consisted of 48 trials (3 refresh rates * 8 duty cycles * 2 repetitions per combination) and six random trials, based on the same logic as for experiment 1. One block lasted roughly 15 min and participants completed between 2 and 10 blocks.

3 | RESULTS

In the following sections, we describe the findings from the two experiments—the first focused on understanding the appearance of phantom arrays and oculomotor impact of shorter duty cycles, and the second focused on understanding the appearance of motion blur at longer duty cycles. A discussion of the implications of both follows.

3.1 | Experiment 1

The goal of experiment 1 was to measure impacts of varying refresh rate and duty cycle on the perception of phantom array artifacts and saccadic eye movement behavior. To quantify the impact of temporal display parameters on the report of phantom array artifacts, we used a repeated measures ANOVA with the factors *refresh rate*

(90, 180, and 240 Hz) and *duty cycle* (5%, 10%, 15%, 20%, 40%, 65%, 70%, and 75%). In line with previous research,[4] we observed a significant effect of duty cycle ($F_{7, 91} = 2.90$, $p = .01$), with a higher chance of perception of the phantom array for lower duty cycles (see Figure 2A). However, we noted a large variability between participants in how often they reported seeing the phantom array artifact, which we will discuss later.

As a next step, we looked at potential impacts on oculomotor control. Because our targets were displaced horizontally, we used the horizontal saccade position error to measure the impact of display parameters on oculomotor targeting abilities (Figure 2B). Negative values in Figure 2B indicate an undershoot of the target, which is typically found in natural behavior[10]. To quantify the influence of the temporal display characteristics, we again used a repeated measures ANOVA with the factors *refresh rate* and *duty cycle.* There was a significant effect of the *duty cycle* of the display on saccade error ($F_{7, 91} = 27.81$, $p < .001$). We observed a greater saccade position error for lower duty cycles, which is consistent with the above described increased probability of perceptual reports of the phantom array artifact observed in our data. In addition, there was some variability across the different refresh rates (main effect refresh rate: $F_{2, 26} = 2.22$, $p = .13$; interaction: $F_{14, 182} = 1.27$, $p = .23$), suggesting that the absolute time the display is illuminated, or persistence, might be also an important factor; for example, a duty cycle of 20% for a 90-Hz display in absolute persistence units is the same as a duty cycle of 40% for a 180-Hz display (2.2 ms). We therefore replotted the data in terms of the persistence (see Figure 2C) and found a strong relationship ($r(24) = .87$, $p < .001$) between persistence and saccade error. Thus, in our task, low duty cycle/persistence values led to a significant, adverse impact on saccade targeting.

As noted above, there was a large intersubject variability about the perception of the phantom array artifact. Most participants barely reported seeing the artifact in any of the trials, despite being trained on seeing the artifact at the start of each session. To visualize the codependence of artifact detection and saccade errors (see Figure 3A), we computed the difference between the probability of reporting an artifact below and above 60% duty cycle (threshold measured previously in Murdison et al.[4]) for each participant and compared this value to the difference in saccade error computed for the same trials. This analysis revealed a reliable effect on saccade error (see points on right side of x-axis), whereas only two participants significantly reported more artifacts for lower duty cycles (see six points—one per participant, per condition—in lower half of y-axis). There was also no significant relationship between the two measurements ($r(42) = .025$, $p = .87$), suggesting that the phantom array was not visible for most of the observers, but there was a consistent subthreshold effect on saccade behavior. The perception of the phantom array was also not related to any changes in visual acuity, measured by the discrimination task (see Figure 3B). Note here that the two participants who strongly perceive the phantom array artifact showed the same changes in visual acuity as all the other participants.

These results raised an important question: Do the negative oculomotor effects of phantom arrays correspond with the ability of observers to resolve visual details even if the phantom arrays themselves are not consistently perceptible? We found that an overall increase in saccade position error correlated with a decrease in the discrimination performance ($r(24) = .74$, $p < .001$; see Figure 3C). The same relationship between position error and duty cycle held when accounting for the final (discrimination) saccades
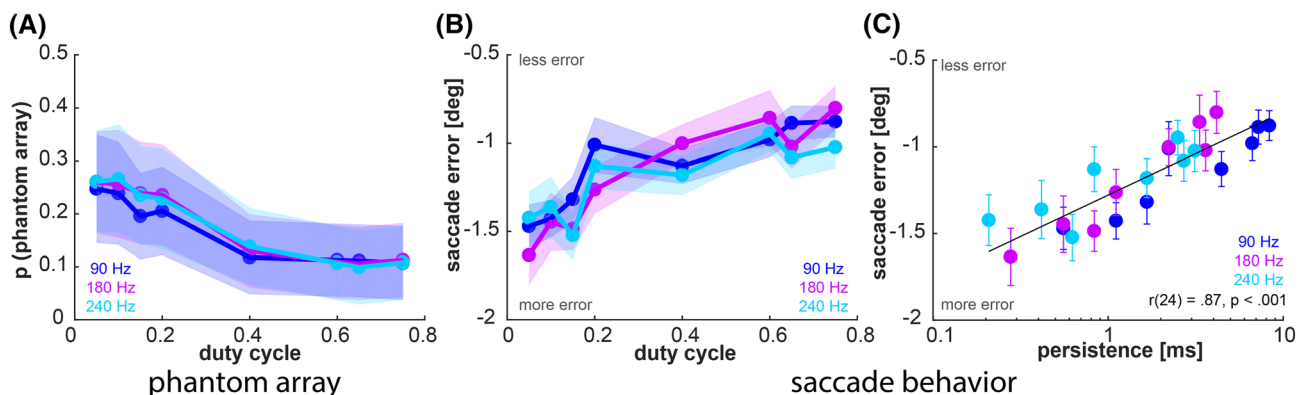

FIGURE 2 Impacts of temporal display characteristics on perception of phantom array and saccade control. (A) Average probability of reporting the perception of a phantom array across different duty cycles and refresh rates. (B) Average horizontal saccade error for the 20 deg saccade for different duty cycles and refresh rates. (C) Saccade error as a function of the persistence of the respective condition. All shaded areas and error bars depict the standard error of the mean
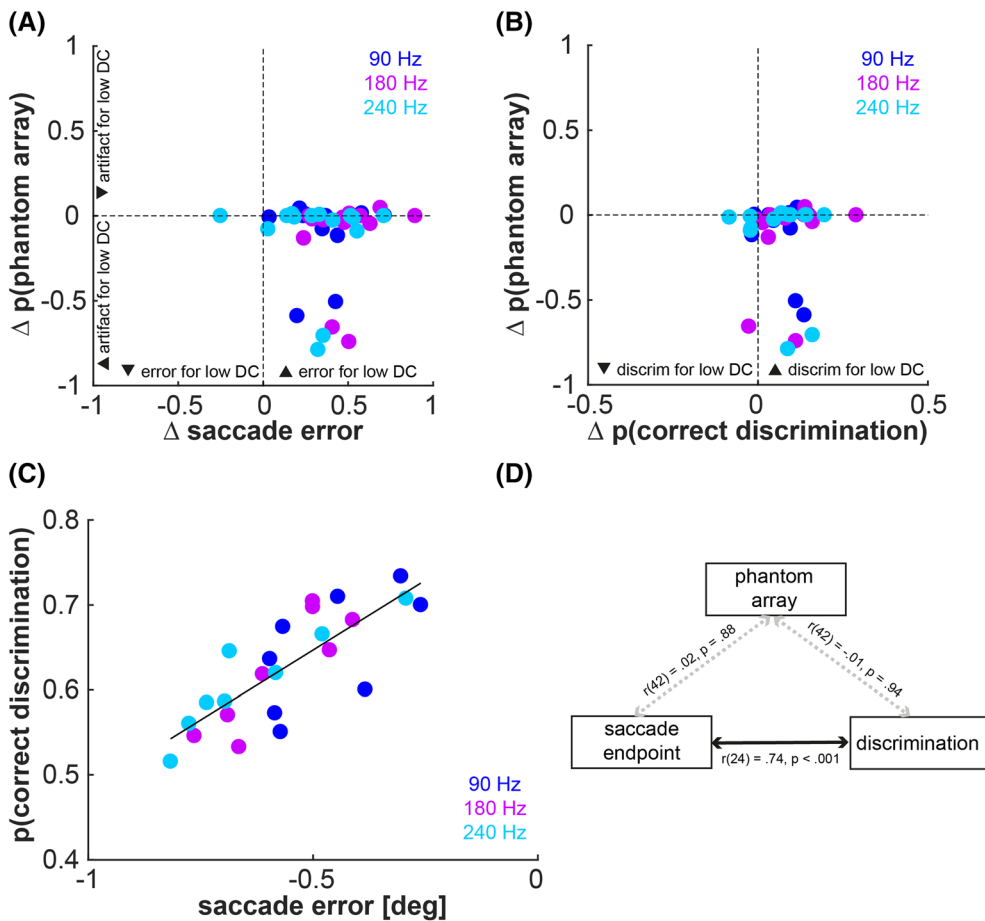
FIGURE 3 Relationship between dependent measures. (A) Difference between <60% and ≥60% duty cycle (DC) for saccade error and phantom array for each participant. Positive values on the horizontal axis indicate a higher saccade error for low duty cycles. Negative values on the vertical axis depict higher probability of reporting a phantom array for low duty cycles. (B) Same depiction as in A, but here, the phantom array effect is plotted against the difference in discrimination performance. (C) Relationship between saccade error and the probability of being correct in the discrimination task. (D) Summary of the relationships between the different dependent variables

($F_{7, 91} = 2.28$, $p = .03$). There was an approximate 20% drop in perceptual task performance between the highest and lowest duty cycles. Together, these results suggest that severe decreases in visual target discrimination is a direct consequence of an altered saccade landing position and not affected by the appearance of a phantom array artifact (see Figure 3D).

3.2 | Experiment 2

The goal of experiment 2 was to understand the impacts of temporal display properties on the perception of motion blur and VOR eye movement behavior. While moving their head sinusoidally, participants were instructed to fixate on a central target for two consecutive stimuli with different duty cycle and refresh rate and then reported which of them appeared blurrier, in a two-interval, forced choice (2IFC) design. We collapsed all trials across participants and determined the minimum blur detection threshold across duty cycles using a one-sided binomial test. The measured blur detection probabilities are shown across different duty cycles and refresh rates in Figure 4A. We found that blur detection probability increased with duty cycle but with a reduced slope for

higher refresh rates. This analysis revealed that for 90 Hz participants were able to consistently detect blur at 15% duty cycle, for 180 Hz at 20% duty cycle and at 240 Hz for 40% duty cycle (all $p < .05$). The difference between the different refresh rates was well explained by the differences in persistence ($r(24) = 95$, $p < .001$, see Figure 3B), suggesting that the crucial variable for blur detection is the display persistence during nonzero head velocity, which is directly proportional to the retinal displacement.

We quantified any oculomotor impacts of physical blur by examining the VOR responses of observers. To this end, we computed the gain, which is equal to the ratio of the eye and head velocity. Thus, a gain equal to 1 indicates a perfect counterrotation of the eyes relative to the head, representing a constant spatial fixation on the target. The average head velocity across all trials was 38.60 deg (± 8.70 deg/s) with average peak velocities of 72.81 deg/s (± 19.97 deg/s). Across all conditions, the gain was close to 1 at 0.86 ± 0.17. On the average values across participants, we performed again a repeated measurement ANOVA with the refresh rate and duty cycle but did not find any significant influence (all p's > .2). Thus, in contrast to the effect on saccade behavior, we did not detect an impact of temporal display parameters on the VOR gain.
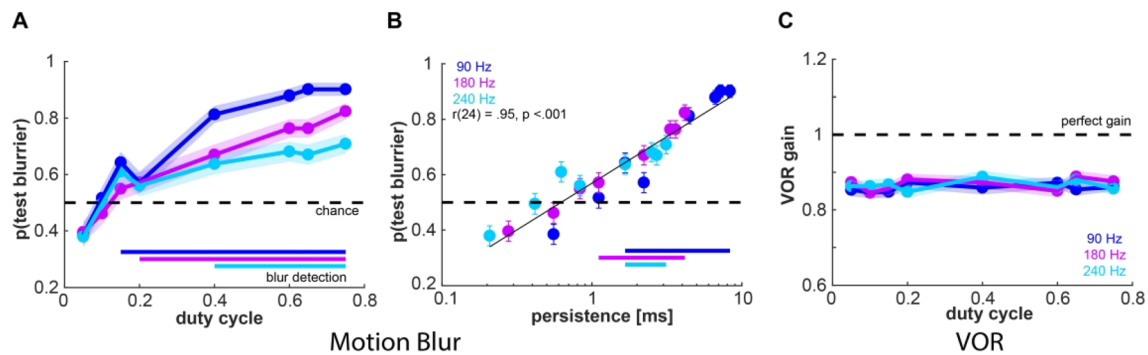
FIGURE 4 Impacts of temporal display characteristics on perception of motion blur and VOR gain. (A) Probability of reporting the test stimulus as blurrier for different duty cycles and refresh rates. Colored lines indicate areas above blur detection threshold per one-sided binomial test ($p < 0.05$). Shaded area represents the standard deviation across trials estimated via sampling the distribution of responses by randomly selecting half of the available trials for $N = 10\,000$. (B) Same data as in A, replotted in persistence units. (C) The average VOR gain across different duty cycles and refresh rates

4 | DISCUSSION

The goal of these two experiments was to understand the impacts of temporal HMD properties (duty cycle and refresh rate) on (1) phantom array perception, (2) saccade targeting, (3) motion blur detection, and (4) VOR gain. We found that although short duty cycles resulted in inconsistent phantom array percepts, they consistently resulted in significant undershoots to saccade targeting, indicating subperceptual threshold effects on participants. Not surprisingly, we also found that longer duty cycles resulted in perceptible motion blur depending on the refresh rate: 15%, 20%, and 40% for 90, 180, and 240 Hz, respectively. Importantly, we found that this did not impact VOR eye movement control. Taken together, these two experiments allow us to make general recommendations for the operating ranges for temporal HMD properties.

In the first experiment, we found significant impacts of shorter duty cycles on saccade targeting even when phantom arrays were imperceptible to the observer. The question arises how saccadic eye movements are affected by the temporal display characteristics. The influence of temporal display characteristic on saccadic eye movements is surprising as the classical view is that saccades are controlled ballistically[17] and visual sensitivity is decreased during them.[18] In fact, there is evidence that visual information during saccades is still processed,[5,19,20] and saccadic control is not completely ballistic[15]; thus, there might be a potential online impact of the temporal characteristics on saccade control. However, because the effect on saccade control was consistent across participants and also present for participants who did not report seeing a phantom array artifact, the oculomotor effects did not appear to impact conscious visual perception of phantom array. In agreement with this point, we also did

not observe any qualitative differences in the saccadic velocity profiles for matched amplitudes between duty cycles, suggesting that oculomotor artifacts are integrated into the planning of the saccade.

Given only sparse visual input about the actual target location, short duty cycles may create uncertainty about the target position presaccadically, which then in turn affects saccade control. As was previously shown and is replicated in our data, saccades typically land short of the target position to some extent (i.e., saccades are hypometric). A given initial hypometric saccade is typically followed by an additional corrective saccade to bring gaze to the spatial target. Because of the initial undershoot, these corrective saccades are typically in the same direction as the saccade, which seems to be by design as the cost of corrective saccades in the opposite direction of the saccade is thought to be especially high in terms of energy consumption and processing time.[10] Thus, if there is added uncertainty about the target location during movement planning, the oculomotor system adopts the strategy of further undershooting the target to avoid incurring the high cost of overshooting.

Based on our current data, we can only speculate about the origin of this potential increase of uncertainty and the effect on saccade control. Due to the typically reported saccadic latencies[21,22] of around 100–200 ms to react to visual stimuli, it seems unlikely that the change in saccade behavior is caused by the artificial copies of the stimulus on the retina although the saccade is in flight. To us, it seems more likely that there is a change in the saccade plan due to the continuous processing of the stimulus during the phase of saccade planning (the 100–200 ms typically considered as latency) which can lead to adjustments of the saccade.[15,23] One explanation could be based on a lower fidelity representation of the target due to the temporally limited input, similar to a

lower contrast (note here that we controlled for target contrast in our study). A second explanation would be that the predictive remapping processes that take place roughly 100 ms before saccade onset are affected by the temporally limited presentation. It is well-known that visuospatial mechanisms in the brain[11–14] use the saccadic motor command signal to predictively compensate for the upcoming changes to the retinal projection—a phenomenon typically referred to as predictive remapping.[11–14] Thus, remapping relies on spatially and temporally accurate estimates of the eye's current and future positions relative to visual input from the oculomotor system. There is evidence that remapping affects perceived stimulus features such as spatial position,[12,13,24] spatial frequency,[18] orientation,[25,26] and color,[27] and it has also been shown to affect the perception of relative stimulus timing.[28] Those potential changes due to the temporally limited visual input about the target location across those remapping processes could also affect saccade control.

Because remapping also affects perception, the differences we observed between the consistent effect on saccade control and the highly variable effect on the perception of phantom arrays presumably could arise from different spatiotemporal processing of the incoming information by perceptual and visuomotor pathways.[29–31] Individual differences in the spatiotemporal sensitivity also can explain why we had a few participants who reported a strong and consistent impact of phantom arrays, whereas other people barely noticed it. Interestingly, we also observed no relationship between the perceptual report of phantom array and changes in discrimination behavior, so the remaining open question was whether the change in saccade landing position does have any negative impacts on the visual user experience. We found that the change in saccadic ending position comes at the cost of a decreased discrimination performance: Spatial acuity at the target is decreased due to its consequent para-foveal location.[6,7,32,33] Our data in combination with those models of spatial acuity across the visual field could now enable interesting work on the prediction of real life consequences of altered oculomotor behavior. Because this decrease in spatial acuity was only related to the change in saccade control and not significantly related to perceptual reports, this suggests two interesting points: First, a potential use of eye movement behavior as a (more) sensitive, implicit, and objective metric to measure impacts of display properties; second, changes in saccadic eye movement performance can lead to decreased visual acuity immediately after the saccade and then need to be corrected by additional movements.

In the second experiment, we quantified motion blur detection as a function of temporal HMD properties. Differences in the strength and detectability of motion blur given a certain refresh rate are well-known,[1,2] but to our knowledge, no one has systematically quantified blur detection in HMDs as we do here. The magnitude of physical blur on the retina is the product of persistence of the display and the display-relative instantaneous velocity of the eye. Thus, due to fact that for the same duty cycle lower refresh rates have higher absolute persistence than high refresh rates, lower refresh rates lead to lower blur detection thresholds (see Figure 4) as the longer illumination of the display leads to a larger spatial extent of the blur during the eye movement. The physical blur as well as additional motion artifacts like aliasing are directly related to the spatial acuity of the observer, for example, which may affect text legibility during display-relative eye motion.[34] However, even if the absolute persistence values were matched, different refresh rates might still result in different blur detectability levels. This is likely because the overall distributions of physical blur on the retina differ due to different numbers of illumination periods during a given movement. Our data can serve as a starting point to understand blur detection thresholds across different duty cycles, but to fully understand blur detection, one would also need to account for the full physiological kinematics of eye and head movements, for example, when computing the retinal blur.

When we investigated the eye movement behavior in the blur task, we did not observe a systematic effect on VOR gain. There is evidence that VOR gain can be affected by long-term changes in visuomotor mapping, for example, with prism adaptation,[35] or higher level factors such as the predictability of head movements.[36] In contrast to saccades that are driven mostly by the incoming visual input, the vestibulo-ocular reflex is controlled by a short vestibular control circuit based on the ongoing head movements.[37] Thus, although changes in the visual input can modify control, the main control input is independent of visual input. Based on our results, the change in incoming visual input in our task due to the additional motion blur does not seem to affect this control circuit. One potential explanation for this observation is that, due to the randomization of individual trials, no constant change in the visual input was present—thereby not invoking any adaptive VOR processes. One may observe differences in VOR gain after being exposed to a significant amount of constant motion blur during every head movement, for example, in a VR game, similar to observations from prism adaptation studies.[35] Although it was beyond the scope of this work, a reasonable next experiment might also investigate how other oculomotor

responses change as a function of retinal motion blur—specifically smooth pursuit.

The present results can be an interesting starting point for considering not only perceptual but also behavioral metrics when evaluating display parameters, though they are not without limitations. First, it needs to be tested how generalizable those effects are across different display types in VR and AR. Although we used an AR display prototype in our set of studies, we hypothesize that one should observe similar effects on a VR display, as the uncertainty about target location should be affected in the same way, given sparsely distributed content. Although for VR displays oculomotor adaptation mechanisms[38] might normalize saccade control and avoid long-term visual discomfort due to full field-of-view input, this may not be the case for additive, AR displays. How oculomotor adaptation might affect movements of the eyes between real, continuously illuminated targets and virtual, discontinuously illuminated targets is an open question. Second, while highly controlled, the tasks used here are highly artificial (e.g., single-axis of head rotation) and used simple visual stimuli (e.g., monochrome and single bit). Thresholds and performance might differ depending on more naturalistic tasks and stimuli. Third, despite controlling for contrast impacts on saccade control,[8,9] the overall brightness differences for the different duty cycles might have affected our results. Because brightness can affect visual acuity,[39] follow-up work should validate those results with matched brightness across different duty cycles.

Despite the limitations, together our experiments can inform the tradeoff of eye movement artifacts and blur artifacts along a continuum of duty cycles. First, we found a reduction of visual acuity at the targeted object due to inaccurate saccadic eye movements. Additionally,

this error may lead to long-term discomfort due to the continual need for additional corrective eye movements. We also found that long duty cycles come with their own costs, for example, by introducing the strong percept of motion blur and a loss in spatial acuity.[1] To quantify the tradeoff and allow for a direct comparison of the two costs, we computed the normalized impact based on changes in saccade error and the probability of detecting motion blur across different refresh rates and duty cycles (Figure 5A). Based on these cost functions, it is possible to estimate an optimal selection of display parameters to minimize both impacts (Figure 5B). When equally weighting both impacts the optimal parameter in our study was at 9% duty cycle for a display running at 90 Hz, 37% duty cycle at 180 Hz, and 80% duty cycle at 240 Hz. One could also easily add different cost functions like energy consumption to take into account additional factors to optimize HMD design. The weighting of the different impacts of temporal display characteristics can and should be optimized depending on the display type (e.g., AR or VR), expected use case and exact temporal constraints of the display.

5 | IMPACTS

- We used a novel, high speed AR-like HMD prototype to quantify the perceptual and oculomotor impacts of duty cycle and refresh rate.
- We found that normal saccadic targeting was consistently adversely affected by shorter duty cycles even when no perceptual phantom array artifact was reported.
- We found minimum duty cycle thresholds corresponding to motion blur detection across different
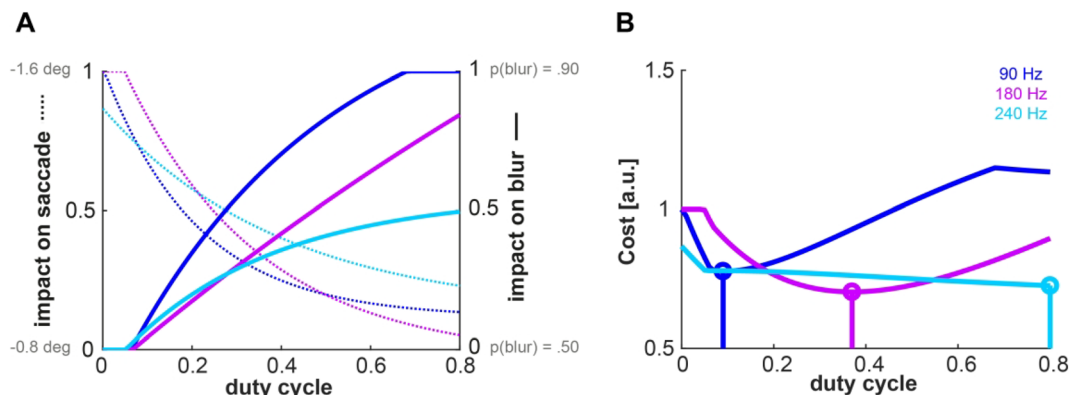

FIGURE 5 Tradeoff of impacts of different duty cycles and refresh rates. (A) Data from Figures 2A and 4A normalized and fitted with an exponential function to estimate the tradeoff between the two measures across different duty cycles. Different colors depict the different refresh rates, consistent with color code in previous figures. (B) Example cost functions by equally weighing the negative impacts on saccade behavior and motion blur. Minima here, represent the best solution to minimize their overall negative impact

refresh rates and found no effect of duty cycle or refresh rate on VOR gain.

- We recommend choosing a duty cycle that minimizes for both the negative oculomotor and perceptual artifacts, depending on the temporal constraints of the HMD.

ORCID

T. Scott Murdison https://orcid.org/0000-0002-7696-9702

REFERENCES

1. Mackin A, Noland KC, Bull DR. The visibility of motion artifacts and their effect on motion quality. In: 2016 IEEE International Conference on Image Processing (ICIP) [Internet]. IEEE; 2016. p. 2435–2439.
2. Regan M, Miller GSP. The problem of persistence with rotating displays. IEEE Trans Vis Comput Graph. 2017;23(4):1295–1301.
3. Hershberger W. Saccadic eye movements and the perception of visual direction. Percept Psychophys. 1987;41(1):35–44.
4. Murdison TS, McIntosh C, Hillis J, MacKenzie KJ. 3-1: Psychophysical evaluation of persistence- and frequency-limited displays for virtual and augmented reality. SID Symp Dig Tech Pap. 2019;50(1):1–4.
5. Schweitzer R, Watson T, Watson J, Rolfs M. The joy of retinal painting: a build-it-yourself device for intrasaccadic presentations. Perception [Internet]. 2019 Aug 3;48(10):1020–1025.
6. Wikler KC, Rakic P. Distribution of photoreceptor subtypes in the retina of diurnal and nocturnal primates. J Neurosci. 1990;10(10):3390–3401.
7. Jonas JB, Schneider U, Naumann GOH. Count and density of human retinal photoreceptors. Graefes Arch Clin Exp Ophthalmol. 1992;230(6):505–510.
8. Doma H, Hallett PE. Dependence of saccadic eye-movements on stimulus luminance, and an effect of task. Vision Res. 1988;28(8):915–924.
9. Ludwig CJH, Gilchrist ID, McSorley E. The influence of spatial frequency and contrast on saccade latencies. Vision Res. 2004;44(22):2597–2604.
10. Lisi M, Solomon JA, Morgan MJ. Gain control of saccadic eye movements is probabilistic. Proc Natl Acad Sci. 2019;116(32):16137–16142.
11. Sommer MA, Wurtz RH. Brain circuits for the internal monitoring of movements. Annu Rev Neurosci. 2008;31:317.
12. Zirnsak M, Steinmetz NA, Noudoost E, Xu KZ, Moore T. Visual space is compressed in prefrontal cortex before eye movements. Nature. 2014;507(7493):504–507.
13. Colby CL, Goldberg ME. The updating of the representation of visual space in parietal cortex by intended eye movements. Science (80-). 1992;255(5040):90–92.
14. Knapen T, Swisher JD, Tong F, Cavanagh P. Oculomotor remapping of visual information to foveal retinotopic cortex. Front Syst Neurosci. 2016;10:54.
15. Gaveau V, Martin O, Prablanc C, Pélisson D, Urquizar C, Desmurget M. On-line modification of saccadic eye movements by retinal signals. Neuroreport. 2003;14(6):875–878.
16. Thaler L, Schütz AC, Goodale MA, Gegenfurtner KR. What is the best fixation target? The effect of target shape on stability of fixational eye movements. Vision Res. 2013;76:31–42.
17. Robinson DA. Models of the saccadic eye movement control system. Kybernetik. 1973;14(2):71–83.
18. Burr DC, Morrone MC, Ross J. Selective suppression of the magnocellular visual pathway during saccadic eye movements. Nature. 1994;371:511–513.
19. Castet E, Masson GS. Motion perception during saccadic eye movements. Nat Neurosci. 2000;3(2):177–183.
20. Boi M, Poletti M, Victor JD, Rucci M. Consequences of the oculomotor cycle for the dynamics of perception. Curr Biol. 2017;27(9):1268–1277.
21. Cisarik PM, Bedell HE, Stevenson SB. The effect of a temporary absence of target velocity information on visual tracking. J Eye Mov Res. 2010;3(4):1–16.
22. Becker W, Jürgens R. An analysis of the saccadic system by means of double step stimuli. Vision Res. 1979;19(9):967–983.
23. Schreiber C, Missal M, Lefèvre P. Asynchrony between position and motion signals in the saccadic system. J Neurophysiol. 2006;95(2):960–969.
24. Cavanaugh J, Berman RA, Joiner WM, Wurtz RH. Saccadic corollary discharge underlies stable visual perception. J Neurosci. 2016;36(1):31–42.
25. Melcher D. Predictive remapping of visual features precedes saccadic eye movements. Nat Neurosci. 2007;10(7):903–907.
26. Murdison TS, Blohm G, Bremmer F. Saccade-induced changes in ocular torsion reveal predictive orientation perception. J Vis. 2019;19(11):1–13.
27. Golomb J, L'Heureux Z, Kanwisher N. Feature-binding errors after eye movements and shifts of attention. Psychol Sci. 2014;25(5):1067–1078.
28. Binda P, Cicchini GM, Burr DC, Morrone MC. Spatiotemporal distortions of visual perception at the time of saccades. J Neurosci. 2009;29(42):13147–13157.
29. Goodale MA, Milner AD. Separate visual pathways for perception and action. Trends Neurosci. 1992 Jan;15(1):20–25.
30. Tavassoli A, Ringach DL. When your eyes see more than you do. Curr Biol. 2010;20(3):R93–R94.
31. Goettker A, Brenner E, Gegenfurtner KR, de la Malla C. Corrective saccades influence velocity judgments and interception. Sci Rep. 2019;9(1):1–12.
32. Banks MS, Sekuler AB, Anderson SJ. Peripheral spatial vision: Limits imposed by optics, photoreceptors, and receptor pooling. JOSA a. 1991;8(11):1775–1787.

33. Watson AB. A formula for human retinal ganglion cell receptive field density as a function of visual field location. J Vis. 2014;14(7):15.

34. Marianovski M, Wilcox LM, Allison RS. Evaluation of the impact of high frame rates on legibility in S3D film. Proc - SAP 2015 ACM SIGGRAPH. Symp Appl Percept. 2015;–67, 73.

35. Jones GM, Guitton D, Berthoz A. Changing patterns of eye-head coordination during 6 h of optically reversed vision. Exp Brain Res. 1988;69(3):531–544.

36. Sprenger A, Wojak JF, Jandl NM, Hertel S, Helmchen C. Predictive mechanisms improve the vestibulo-ocular reflex in patients with bilateral vestibular failure. J Neurol. 2014;261(3): 628–631.

37. Dichgans J, Bizzi E, Morasso P, Tagliasco V. The role of vestibular and neck afferents during eye-head coordination in the monkey. Brain Res. 1974;71(2–3):225–232.

38. McLaughlin SC. Parametric adjustment in saccadic eye movements. Percept Psychophys. 1967;2(8):359–362.

39. Watson AB. High frame rates and human vision: a view through the window of visibility. SMPTE Motion Imaging J. 2013;122(March 2013):18–32.

AUTHOR BIOGRAPHIES

Alexander Goettker completed a bachelor and master's degree in psychology at the Justus Liebig University Giessen in Germany. Currently, he is completing his PhD in Giessen together with Prof. Karl Gegenfurtner on oculomotor control. His doctoral research is on the interaction of saccadic and pursuit eye movements and how the brain reconstructs our perception of the world during eye movements. During his PhD, he had the chance to visit of Prof. Gunnar Blohm at Queen's university in Kingston, Canada, and Prof. Eli Brenner in Amsterdam, Netherlands. Additionally, he was able to work as a research intern at Facebook to learn about the applied perspective of basic neuroscience.

Kevin J.MacKenzie is the Scientific Research Lead for the Applied Perception Science team in the AR/VR organization at Facebook. He received his PhD from York University's Centre for Vision Research and a post-doctoral fellowship at Bangor University. He has held research positions at Microsoft as a Design Researcher, and Human Factors Engineer, supporting the development of Microsoft Hololens and Facebook as a Research Scientist and Research Lead at Facebook Reality Labs and AR/VR.

T.Scott Murdison completed his undergraduate degree at Queen's University in Chemical Engineering and received a PhD in Neuroscience from Queen's in 2016. His doctoral research, advised by Dr.Gunnar Blohm, focused on understanding neural and oculomotor mechanisms for 3D visuospatial stability during movements of the eyes and head. During his PhD, he also enjoyed a year-long research stay in Germany in the lab of Prof. Frank Bremmer at Philipps-Universitaet Marburg. He subsequently joined Facebook Reality Labs as a Postdoctoral Research Scientist, designing psychophysical studies and building models of human vision to better understand perception during user motion in virtual and augmented reality. Now, a Research Scientist at Facebook, he continues this work to help drive future display technologies.