Effects of a Monocular Laser-Based Head-Mounted Display on Human Night Vision

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ABSTRACT

Head-mounted displays (HMDs) are expected to dominate the market of wearable electronics in the next 5 years. This foreseen proliferation of HMDs yields a plethora of design opportunities for revolutionizing everyday life via novel use cases, but also generates a considerable number of substantial safety implications. In this work, we systematically investigated the effect of a novel monocular laser-based HMD on the ability of our participants to see in low ambient light conditions in lab settings. We recruited a total of 19 participants in two studies and performed a series of established vision tests while using the newly available Focals by North HMD. We tested our participants' night vision after being exposed to different levels of laser luminous power and laser colors while using Focals, either with one or both eyes open. Our results showcase that the image perceived by the non-exposed eye compensates for the loss of contrast sensitivity observed in the image perceived by the laser-exposed eye. This indicates that monocular laser-based HMDs, such as Focals, permit dark adaptation to occur naturally for the non-exposed eye.

CCS CONCEPTS

•Human-centered computing → Empirical studies in HCI;

KEYWORDS

Head-mounted displays, Laser light projection, Scotopic vision, Human Factors

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Figure 1: Focals head-mounted display. The light is emitted by the projector encased in the right temple, and it reaches the right eye after being reflected by a hologram embedded in the right lens.

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1 INTRODUCTION

Recent advances in optics and hardware miniaturization have rendered eyewear the next frontier for Wearable and Ubiquitous Computing (e.g., Google Glass[1], Microsoft HoloLens[2], Magic Leap One[3] and Focals[4] by North), essentially materializing the vision of Augmented Reality (AR) [2]. In the year 2022, a total of over 80 million HMD units is expected to ship, up from 28.4 million units sold in 2018[5]. This indicates that an uptake in HMD usage is imminent, yielding a unique design space for experimentation and product development.

As HMDs continue to evolve, various taxonomies and classifications have been proposed in literature [20]. Among many criteria, contemporary HMDs can most prominently be

[1]https://www.x.company/glass
[2]https://www.microsoft.com/en-us/hololens
[3]https://www.magicleap.com/magic-leap-one
[4]https://www.bynorth.com
[5]https://www.gartner.com/en/newsroom/press-releases/
2018-11-29-gartner-says-worldwide-wearable-device-sales-to-grow-

grouped by their visual input modality (binocular vs. monocular), their display technology (laser light, LCD / OLED, micro-display gratings, etc.), and ultimately, their reality domain (Virtual Reality–VR vs. Augmented or Assisted Reality–AR). For example, Microsoft HoloLens is equipped with a binocular transparent light display that utilizes 3 layers of diffractive gratings for producing a colored image. Microsoft HoloLens and its wide field of view is said to couple the best features of both VR and AR for delivering MR (Mixed Reality). On the contrary, Google Glass comes with a lightweight monocular Liquid Crystal on Silicon (LCoS) display mounted on a lightweight frame in front of user's right eye. Google Glass is considered an AR device and is currently used in assembly lines for boosting productivity and training new recruits. To date, none of the aforementioned HMDs has experienced wide user adoption. Recent work in the field of privacy and social implications of technology has raised serious concerns over the social acceptability of contemporary HMDs, identifying reduced social acceptability as a detrimental factor to wider user adoption [9, 14].

Drawing on the social implications that stem from the use of HMDs in everyday life settings, North Inc. designed and developed Focals, a monocular and lightweight laser-based HMD that resembles almost entirely a typical pair of glasses (see Figure 1). Focals by North utilizes a laser projector, encased in the right temple of the eyewear frame that projects 4 laser beams of light onto the right lens. The right lens reflects the laser beams onto the user's right eye via a hologram, while the left eye view remains unobstructed. Hence, Focals features a laser light display that is fundamentally different from other consumer-oriented HMDs, such as Google Glass and Microsoft Hololens.

Evaluating safety is a critical component in the course of delivering a product of mainstream adoption. As such, assessing the effects of Focals' novel display technology when operated at night emerges as high priority. Human vision is notorious for being particularly slow to adapt to low ambient light levels [13], and can be disrupted by bursts of light such as those emitted from monocular HMDs [19]. To the best of our knowledge, no previous work has explored the impact of laser display technology for monocular HMDs on human night vision. Understanding the effects of such technology is a necessary prerequisite for safely reaping their promised benefits (e.g., turn-by-turn navigation with a HMD during night driving [4]). This work presents findings from two studies that inquired into the effects of laser light, both in brightness (luminous power) and color (wavelength), on human night vision when projected from a monocular laser-based HMD such as Focals.

2 RELATED WORK

The ability of the human eye to adapt to conditions of low ambient light is ascribed to the presence of light-sensitive pigments in the rods (night, or scotopic vision) and cones (colored, or photopic vision) which are photoreceptor neurons found in the human retina. When exposed to light, the pigments undergo a continuous process of destruction and regeneration, with the pigments of the rods being more susceptible to light than the pigments of the cones [13]. Dark adaptation, the underlying process of human night vision, occurs in two distinct stages: (a) the early dark adaptation stage, lasting for the first 5–8 minutes, during which the cones adapt rapidly to low ambient light levels [1], and (b) the dark adaptation stage, initiated after early dark adaptation and continuing for up to 30 minutes later, during which the rods adapt gradually to low ambient light levels [13]. The opposite occurs when the human eye is exposed to conditions of high ambient light from prior conditions of low ambient light. This process is known as light adaptation and it is substantially faster than dark adaptation [8].

It is generally considered that scotopic vision occurs in ambient light levels of below .003 lux (or .003 lumen per square meter) and photopic vision above 3 lux, with mesopic vision lying in between (.003–3 lux) [21]. However, not all light colors (wavelengths) affect equally the aforementioned vision types. For example, scotopic vision is particularly sensitive to blue light (~507 nm) and less so in the red spectral range (~700–635 nm) [6]. In contrast, photopic vision displays a maximum sensitivity in the green spectral range (~555 nm) [21]. Prior work has also shown that age plays a significant role in the sharpness of scotopic vision, with older subjects (40–47 years) requiring 150 % more ambient light to preserve the same levels of visual acuity (the ability to discern shapes of objects) as younger subjects (20–24 years) [13]. In fact, age appears to substantially influence the rate at which dark adaptation occurs, adding on average 2.76 min/decade for reaching the baseline of scotopic sensitivity [7].

The aforementioned effects on human night vision have been taken into consideration when the first HMDs were introduced in the 1960s in military simulators, primarily for far field visualization [20]. Ever since, human factors experts and ophthalmologists have identified a series of vision issues associated with the use of monocular HMDs for military purposes, such as disrupting binocular vision (binocular rivalry) [16], and "brightness averaging", where the brightness of the image perceived by the dark-adapted eye may be combined with the brightness of the image perceived by the light-adapted eye (i.e., the one exposed to the HMD) [10]. Rash provides a comprehensive 25-year summary of the visual issues associated with the use of monocular HMDs in the military [19]. For the consumer HMDs, no significant differences have been found between the effects of HMDs on human vision and those of a typical computer monitor [17], but HMD usage has been found to induce higher eye dryness than smarthphone usage [5]. However, contemporary monocular HMDs, such as Google Glass, have been found to produce a significant "disability glare" to the exposed eye in low ambient light levels, while decreasing contrast sensitivity (the ability to distinguish objects from the background) for both eyes [11]. Thus, it quickly becomes apparent that the display technology plays an important role in the severity of the HMD effects on human night vision. In transparent HMDs such as Focals, the binocular rivalry is diminished by having the view of both eyes binocularly fused with additional imagery projected onto one eye [23]. However, the novel use of a laser light projector generates demands for thorough evaluation, especially if one considers the high variability in the visual complexity of real-world backgrounds when it comes to everyday life tasks (e.g., night-driving [4]).

3 STUDY DESIGN

We investigated how Focals users see in the dark in two user studies. The 1st study aimed at evaluating the effects of monocular laser-based HMDs when both eyes are used in conditions of low ambient light. However, we still wanted to identify any effects on the exposed eye in isolation for forming a better understanding over any implications introduced by Focals' novel laser display technology. Hence, in the 2nd study, we measured the impact of monocular laser-based HMDs on the eye that receives the emitted light. In these studies, we formulated and tested the following hypotheses:

H1. *A high laser luminous power level affects more negatively scotopic vision in low ambient light levels than a low laser power level does.* Prior work has shown that during the use of traditional (non-transparent) monocular displays, the light-adapted eye (the exposed eye) may reduce the contrast sensitivity of the dark-adapted eye (the non-exposed eye) in conditions of low ambient light (brightness averaging) [10]. In fact, recent work in transparent LCoS displays has unveiled a significant drop in contrast sensitivity in low ambient light conditions for both the non-exposed and the exposed eye, an effect known as the "disability glare" [11].

H2. *Red laser color will affect scotopic vision the least negatively in low ambient light conditions.* Scotopic vision is less sensitive to red light than it is to blue light, and thus less disrupted by red light [6]. Thus, we expect a significantly smaller drop in visual acuity and contrast sensitivity for red laser color as opposed to purple, which is closer to the wavelength of blue light.

H3. *Scotopic vision when only relying on the exposed eye should be significantly impaired as opposed to relying on both eyes, regardless of laser light color.* When only the exposed eye is used, we expect the "disability glare" [11] to cause a significantly higher disruption to its scotopic vision than when both eyes are used. That in turn will result in a significant loss of visual acuity and contrast sensitivity. However, we expect that any detrimental effects on the scotopic vision of the exposed eye will be smaller when under red laser light as opposed to purple [6].

(a) (b)

Figure 2: Vision test chart examples of (a) visual acuity (Snellen test [3]) and (b) contrast sensitivity (Pelli-Robinson test [18]) we used in the study.

Participants

We recruited a total of 19 participants (9 were female) with an average age of 28 years ($SD = 7.336$) years. The 1st study involved 11 participants, the 2nd study 8 participants. All participants were office workers and had limited or no experience in using HMDs. Participants were recruited on the basis of having no visual impairments, hence we consider all participants had an innate 20/20 visual acuity level.

Measures

We used two widely employed standardized measures of human vision as our dependent variables:

1. *Visual acuity* is used for describing the clarity of vision that depends on factors such as the sharpness of the retinal focus, the health of the retina and the sensitivity of the interpretative faculty of the brain [22]. A 20/20 vision characterizes a normal visual acuity measured at a distance of 20 feet [3]. The lower the score over 20, the better the vision. Visual acuity is measured in a standardized procedure by using Snellen test charts (see Figure 2a), widely adopted by ophthalmologists for determining

visual deficits (e.g., myopia) and prescribing corrective lenses. Visual acuity is known to decrease under conditions of low luminance [13].
2. *Contrast sensitivity* describes the limit between what is visible and invisible by distinguishing between smaller and smaller increments of light versus dark contrast [18]. Contrast sensitivity is measured by standardized Pelli-Robinson test charts that display letters of decreasing contrast but not size [18] (see Figure 2b). The letters of the top line have the highest contrast, and the letters of the bottom line have the lowest. A Pelli-Robinson score of 2 indicates normal contrast sensitivity of 100 % — the higher the score, the better the contrast sensitivity. Normal contrast sensitivity values at 2.5 % contrast range between 0.3–0.8 and are affected by age [12].

Procedure

For both studies, we welcomed participants to the lab and asked them to take a dedicated seat, placed at the appropriate distance from a wall for the size of our vision test charts. After participants completed the demographics data collection form, we tested that they could see the Focals' display by using a test grid, a blank test image used for HMD calibration. Participants were adjusted in the chair so as to see the vision test charts directly in their line of sight, and the Focals display slightly to the right of their direct line of sight. Next, we extinguished any source of light (including Focals), and waited in the dark for 5 minutes during which participants' vision should go through a stage of rapid dark adaptation to low ambient light conditions [1]. We limited this time to 5 minutes (down from 30 reported in literature for full dark adaptation), since this was a good compromise for achieving sufficient levels of scotopic vision and not fatiguing the participants with lengthy trials. After participants were adapted to conditions of low ambient light, we were ready to proceed with our experiments, where we tested the following independent variables:

1. *Ambient light.* One lux is equal to one lumen (lm) per square meter (lm/m^2), according to the International System of Units. A full moon on a clear night produces 0.05–0.3 lux, whereas office lighting ranges between 320 and 500 lux [15]. We set the luminance in the lab to be either (a) *low* (.1 lux) or (b) *high* (1 lux) using a dedicated LED lamp and a 180 degree light meter equipped with a cosine filter. We purposefully tested our participants in these ambient light conditions since they resemble most frequently encountered low-light conditions (e.g., during driving or walking outside at night), on the verge between scotopic and mesopic vision [21].

<table>
<tr><th>Ambient light (lux)</th><th>Laser color & luminous power (lm)</th><th>Eye mode</th></tr>
<tr><td colspan="3">5 minutes dark adaptation</td></tr>
<tr><td>low (.1)</td><td>display-off
red-low (.0025)
red-high (.01)</td><td>both and single</td></tr>
<tr><td>high (1)</td><td>display-off
red-low (.0025)
red-high (.01)</td><td>both</td></tr>
<tr><td colspan="3">5 minutes dark adaptation</td></tr>
<tr><td>low (.1)</td><td>display-off
red-low (.0025)
purple-low (.0025)
orange-low (.0025)
white-low (.0025)</td><td>both and single</td></tr>
</table>

Table 1: Order of our experimental conditions. Note the "high (1 lux)" condition was skipped in the 2nd study.

2. *Luminous power.* The HMD laser was tested in 3 different conditions: (a) *display off*, (b) a *low power* (.0025 lm), and (c) a *high power* (.01 lm) square of red light displayed.
3. *Laser color.* We tested our participants in 4 distinct laser color conditions: a (a) *red* (~700–635 nm), (b) *orange* (~635–590 nm), (c) *purple* (~450-400 nm), and (d) *white* (~700–400 nm) square of light displayed.
4. *Eye mode.* We tested participants' night vision when using Focals with (a) *both eyes* open (1st study), and (b) *single eye* open (the exposed eye, 2nd study), covering the non-exposed eye with an eye-patch.

The condition order could not be random, since we had to conserve the participants' achieved dark adaptation level. Hence, we tested the conditions in the order presented in Table 1. In both studies and for each condition, participants' scotopic vision was measured by a series of visual acuity and contrast sensitivity tests administered after each experimental condition (we used different charts each time to avoid learning effects). Scores were recorded on paper form to abstain from using a screen and maintain ambient light levels stable.

4 RESULTS

Before proceeding to any statistical analyses, we first inquired into the effect of our participants' age on their visual acuity and contrast sensitivity, since age influences night vision substantially [7, 13]. For this, we divided our participants in three age groups, A (20–27 years), B (28–35), and C (> 38 years), and we conducted two non-parametric

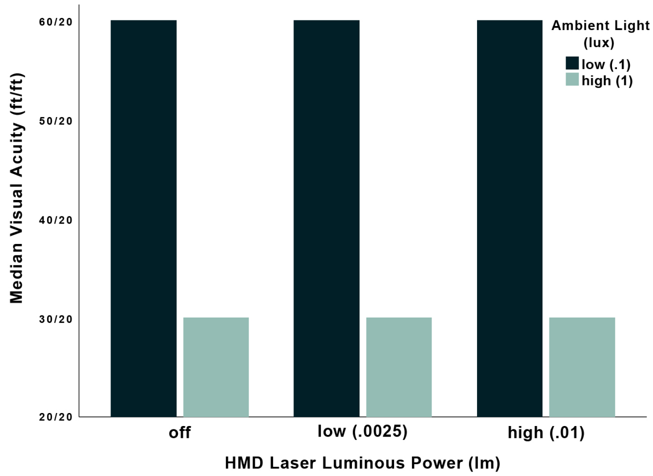

Figure 3: Median visual acuity values for both eyes open, for laser power and ambient light levels. Participants performed significantly better in higher luminance conditions. Laser power had no significant effect on participants' visual acuity in both low and high luminance conditions.

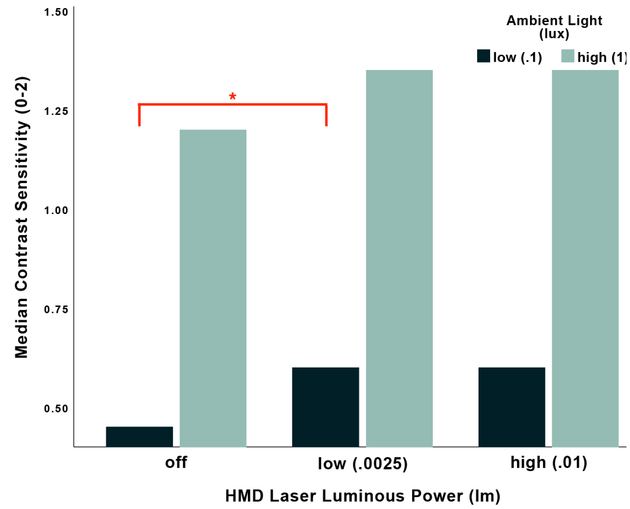

Figure 4: Participants' contrast sensitivity for both eyes open, for laser power and ambient light levels. Contrast sensitivity was significantly better in high than in low ambient light conditions. Low laser power seemed to affect significantly positively our participants' contrast sensitivity in low luminance conditions, but this may be due to the left eye continuing to dark-adapt.

Kruskal-Wallis H tests with visual acuity and contrast sensitivity as dependent variables, and age group as independent. The tests revealed no significant difference in both visual acuity ($\chi^2(2) = 4.796$, $p = .091$) and contrast sensitivity ($\chi^2(2) = 3.04$, $p = .219$) among all three age groups, indicating that the age of our participants did not influence their night vision significantly.

Luminance and Luminous Power Effects

First, we tested the effect of ambient light (low: 0.1 lux vs. high: 1 lux) on participants' night vision. Wilcoxon signed-rank tests between high and low luminance conditions displayed significant differences in participants' visual acuity ($Z = -3.066$, $p < .05$) and contrast sensitivity ($Z = -2.971$, $p < .05$) in overall. Expectedly, in high luminance conditions, visual acuity ($Mdn = 30$) and contrast sensitivity ($Mdn = 1.2$) were significantly better than in low luminance conditions ($Mdn = 60$ and $Mdn = .45$ for acuity and contrast, respectively), when both eyes were open (see Figures 3 and 4).

Next, we investigated the effect of laser power (i.e., off, low: .0025 lm and high: .01 lm) on visual acuity and contrast sensitivity, for both low and high ambient light levels, respectively. Non-parametric Friedman tests showed no significant differences in visual acuity for all laser power levels in both low ($\chi^2(2) = 3.2$, $p = .202$) and high ($\chi^2(2) = 1$, $p = .607$) ambient light conditions, with both eyes open (see Figure 3). However, non-parametric Friedman tests displayed significant differences in contrast sensitivity for different laser power levels in low ($\chi^2(2) = 7.8$, $p < .05$) but not in high ($\chi^2(2) = 1$, $p = .607$) ambient light conditions, when both eyes are open (see Figure 4). In particular, post-hoc Wilcoxon signed-rank tests using the Bonferroni correction revealed a significant difference in the contrast sensitivity between laser-off and low-laser power ($Z = -2.46$, $p < .05$), but not between laser-off and high-laser power levels ($Z = -1.811$, $p = .07$) or low-laser and high-laser power ($Z = -1$, $p = .317$), in low ambient light and when both eyes were open (see Figure 4). Notably, median contrast sensitivity scores were .45 for laser-off, and .6 for both low-laser and high-laser power levels, in low ambient light conditions and when both eyes were open. This potentially indicates that laser power has a positive effect on participants' contrast sensitivity that manifests during conditions of low ambient light and when both eyes are open (**H1**). However, a more likely explanation is that the non-exposed eye continued to adapt to low ambient light levels, and thus gradually yielding better results throughout the study.

Single-Eye Effect. To investigate the effects of laser power on the single exposed eye, we ran a 2nd study with 8 different participants in the low ambient light condition (.1 lux), be it the most challenging. Participants were exposed to multiple laser light power levels (i.e., off, low: .0025 lm and high: .01 lm) using Focals in low luminance conditions only, (a) with both eyes open, and (b) with one eye[6] open, while measuring

[6]The right eye – the one receiving light from the HMD laser.

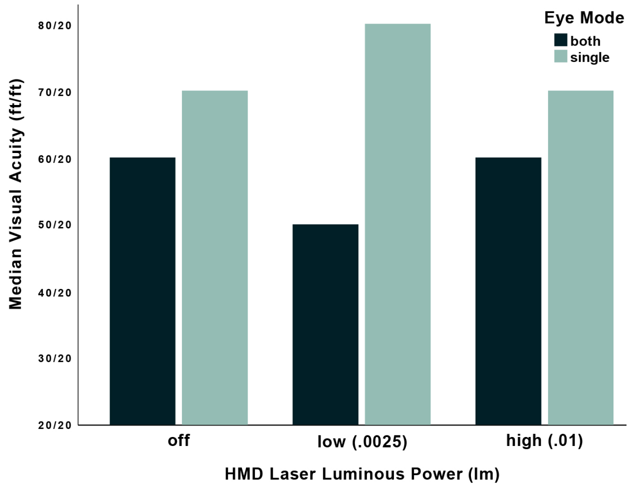

Figure 5: Visual acuity was better when both eyes were open as opposed to a single (exposed) eye, when using Focals in conditions of low ambient light (.1 lux).

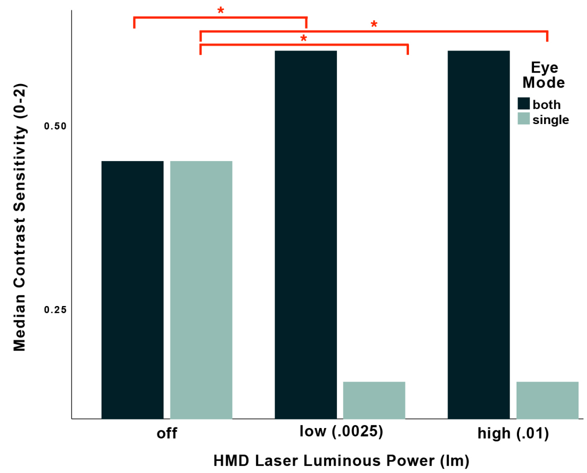

Figure 6: Contrast sensitivity was significantly higher when both eyes were open as opposed to using a single eye, when using Focals in conditions of low ambient light (.1 lux). Contrast sensitivity is significantly higher under low laser power (.0025 lm) when both eyes are open but not with a single (exposed) eye.

their visual acuity and contrast sensitivity levels. Wilcoxon signed-rank tests displayed significant differences between "both-eyes" and "single-eye" modes for both visual acuity ($Z = -3.714$, $p < .001$) and contrast sensitivity ($Z = -3.76$, $p < .001$) (see Figures 5 and 6, respectively). As expected, this indicates that participants' vision was in overall significantly impaired when only relying on a single (exposed) eye (**H3**).

Next, we investigated the effect of laser power level (off, low: .0025 lm and high: .01 lm) on visual acuity and contrast sensitivity for "both-eyes" and "single-eye" modes. Similarly to previous findings, non-parametric Friedman tests displayed no significant difference in participants' visual acuity ($\chi^2(2) = .5$, $p = .779$) for different laser power levels (off, low and high), but a significant difference in contrast sensitivity ($\chi^2(2) = 8.538$, $p < .05$) when both eyes were used in low luminance conditions. In particular, post hoc Wilcoxon signed-rank tests using the Bonferroni correction revealed a significant difference in contrast sensitivity scores between high-laser ($Mdn = .675$) and laser-off ($Mdn = .45$) levels ($Z = -2.46$, $p < .05$), but not between low-laser ($Mdn = .6$) and laser-off ($Z = -1.667$, $p = .096$), or between high-laser and low-laser levels ($Z = -1.414$, $p = .157$) (see Figure 6). This result, though strange, is in fact inline with the aforementioned results in the 1st study (**H1**).

Interestingly, non-parametric Friedman tests revealed no significant difference in participants' visual acuity scores ($\chi^2(2) = 2.8$, $p = .247$) for different laser power levels (see Figure 5), but a significant difference in contrast sensitivity scores ($\chi^2(2) = 8.87$, $p < .05$) when a single eye was used (see Figure 6). In particular, post hoc Wilcoxon signed-rank tests using the Bonferroni correction revealed significant differences in contrast sensitivity scores between laser-off ($Mdn = .45$) and low-laser ($Mdn = .15$) levels ($Z = -2.070$, $p < .05$) and between laser-off and high-laser ($Mdn = .15$) levels ($Z = -2.271$, $p < .05$), but no significant difference between low-laser and high-laser levels ($Z = -.577$, $p = .564$) (see Figure 6). These results indicate that laser power impaired contrast sensitivity when participants used a single eye, but not when using both their eyes (**H3**).

Laser Light Color Effects

Since low ambient light conditions are more challenging, we tested the effects of different laser light colors on human night vision, when using Focals with a low laser power level (.0025 lm) and in low luminance (.1 lux). Particularly, we tested our participants' night vision when exposed to *red*, *orange*, *purple* and *white* laser light colors, and *no light* at all (laser-off). However, non-parametric Friedman tests displayed no significant differences in visual acuity ($\chi^2(4) = 2.476$, $p = .649$) or contrast sensitivity ($\chi^2(4) = 3.184$, $p = .527$) for all the laser light colors tested. This indicates that all 4 different laser light colors we tested had no significant influence on human night vision, as compared to seeing no light, when using a monocular laser-based HMD with both eyes open (**H2**).

Single-Eye Effect. In the 2nd study, we examined the effect of different laser light colors in respect to eye mode ("both-eyes" vs. "single-eye"), under exactly the same settings: low ambient light (.1 lux) and low laser power level (.0025 lm).

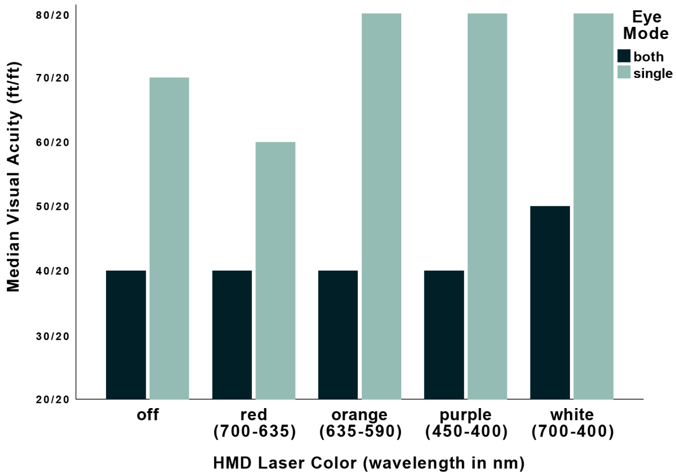

Figure 7: Visual acuity appears better when both eyes are used in contrast to using a single eye. Different laser light colors do not impact significantly visual acuity when either both or a single (exposed) eye are open.

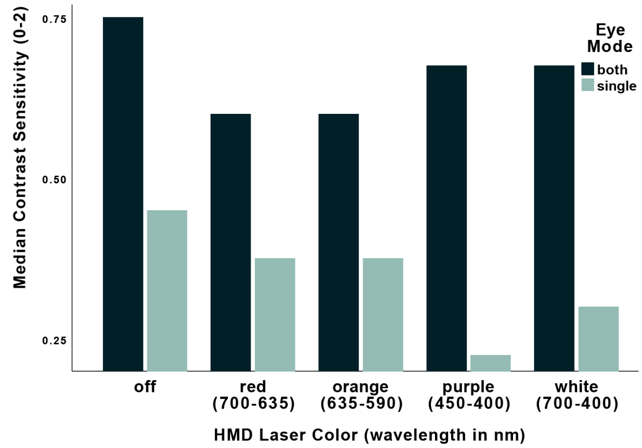

Figure 8: Contrast sensitivity is improved when both eyes are open in contrast to a single eye when using Focals. Different laser light colors do not affect significantly contrast sensitivity when either both or a single eye are open.

Wilcoxon signed-rank tests displayed significant differences between "both-eyes" and "single-eye" modes, for both visual acuity ($Z = -5.422$, $p < .001$) and contrast sensitivity ($Z = -5.226$, $p < .001$) (see Figures 7 and 8). As expected, these results are consistent with the aforementioned findings in that laser light in overall (even in different colors) as emitted when using a monocular laser-based HMD impairs significantly human night vision when relying on a single eye (**H3**). Next, we investigated the effect of laser light color (i.e., red, orange, purple, white and no light) on visual acuity and contrast sensitivity in a separate fashion for "both-eyes" and "single-eye" modes. Similar to previous results, non-parametric Friedman tests displayed no significant differences in participants' visual acuity ($\chi^2(4) = 5.667$, $p = .225$) and contrast sensitivity ($\chi^2(4) = 3.093$, $p = .542$) due to exposure to different laser light colors when using Focals with both eyes open (see Figures 7 and 8). Similarly, but with only one eye open, non-parametric Friedman tests displayed no significant difference in participants' visual acuity ($\chi^2(4) = 5.333$, $p = .255$) and contrast sensitivity ($\chi^2(4) = 7.061$, $p = .133$) as result of being exposed to different laser colors while using Focals (see Figures 7 and 8). These results show that laser light color does not impact significantly human night vision during the use of a monocular laser-based HMD in low ambient light conditions. (**H2**).

5 DISCUSSION

Overall, our early findings are in line with prior work in literature, indicating that the conditions of low ambient light we generated in the lab permitted the manifestation of well-known phenomena associated with human night vision. In particular, 5 minutes in the dark appeared to be sufficient for triggering the early stages of dark adaptation for our participants, instead of 30 for complete dark adaptation [1, 13]. In fact, this allowed for performing our trials in a timely manner, while more realistically recreating conditions of daily life when our eyes continuously struggle to adjust to highly varying ambient light levels (e.g., move in and out a dark room). Moreover, the low (.1 lux) and high (1 lux) ambient light levels we tested, appeared to be on the verge of where scotopic and mesopic vision manifest [21]. This allowed us to form a night vision baseline that corresponds to low ambient light conditions encountered in everyday life (e.g., night driving) [15].

After establishing a night vision baseline, we were able to investigate the effects of the laser light projected from Focals. Our results are somewhat surprising, particularly when it comes to our 1st hypothesis, in that higher laser power levels should negatively affect night vision in conditions of low ambient light (**H1**). However, we found no significant effect for all laser power levels (off, low and high) on participants' visual acuity, but a significant *positive* effect of low laser power on participants' contrast sensitivity, when both eyes were used in conditions of low ambient light. Interestingly, we were able to reproduce the same effect in the 2nd study with a different set of participants under the same conditions. These results are contrary to prior findings in literature, where the light emitted by a monocular HMD has been found to decrease contrast sensitivity for both eyes ("disability glare") [11]. When we tested the exposed eye in isolation and in conditions of low ambient light, we did find a significant drop in both visual acuity and contrast sensitivity due to the light emitted by Focals, as previously hypothesized (**H3**). Hence, any contrast sensitivity increase cannot be ascribed to the exposed-eye per se. Given that we tested our conditions after a short 5-minute dark adaptation period, it is possible that the non-exposed eye continued to adapt to low ambient light levels, even after we had initiated the experiments. This would explain why we observed an increase in contrast sensitivity during the low laser power condition. By abductive reasoning, these findings suggest that the image perceived by the non-exposed eye compensates for the loss of contrast sensitivity observed in the image perceived by the laser-exposed eye [10].

Laser light color (red, purple, orange, and white) was found to bear no effect on participants' night vision in conditions of low ambient light in terms of visual acuity and contrast sensitivity when both eyes are open (**H2**). In fact, the same trend was observed when testing the exposed eye under different laser light colors in isolation. These results seem to contradict prior findings in literature where scotopic vision has been found to be the most sensitive to the blue light as opposed to red [21], However, we did not test pure blue light, but purple instead. We attribute this finding to the low ambient light threshold we used (.1 lux), perhaps causing night vision to operate on the border between scotopic and mesopic, and thus bearing sensitivity to colors we did not test.

6 CONCLUSION

The innate form factor of Head-Mounted Displays (HMD) grants them the unique privilege to interpose with the most highly-regarded human sense: our vision. This yields exciting novel design potential, but also generates immense demands for evaluating HMD effects in a systematic fashion, particularly as display technologies keep evolving. In this work, we systematically evaluated the effects of the newly debuted Focals by North, a monocular and entirely transparent laser-based HMD, on human night vision. Our results showcase that the non-exposed eye maintains its contrast sensitivity levels when using Focals, while unveiling that the different laser light colors we tested have no significant effects participants' night vision. This indicates that monocular laser-based HMDs, such as Focals, permit the dark adaptation to occur naturally for the non-exposed eye, a feature that could bear a strategic advantage over other display technologies in challenging everyday life settings such as driving.

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