Light Filtering Lenses and Visual Photosensitivity in Individuals With Traumatic Brain Injury

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Purpose. The purpose of this study was to assess visual photosensitivity using the Ocular Photosensitivity Analyzer (OPA) with and without light filtering lenses in individuals with traumatic brain injury (TBI) and non-TBI controls.

Methods. This cohort study included 46 individuals with TBI ($n = 46$) and without TBI ($n = 46$) assessed from May 2021 to August 2023 at a large academic tertiary center. Visual photosensitivity thresholds (VPTs) were measured at two visits (≥1 month apart) under four lens conditions: no lens (NL), plano lenses (PLs), FL-41 lenses (FLs), and gray-filtering lenses (GLs). Lower VPTs indicate greater visual photosensitivity.

Results. Participants with TBI had significantly lower VPTs compared with non-TBI controls across all lens conditions at the initial visit (TBI: PL = 1.6 ± 0.9, FL = 1.9 ± 0.9, and GL = 1.9 ± 1.0; and non-TBI: PL = 2.5 ± 0.9, FL = 2.8 ± 0.9, and GL = 2.8 ± 0.9 log lux, $P < 0.05$). Both groups showed improved (higher) VPTs with FLs and GLs compared with NL and PL conditions. Results were repeatable at the second visit (intraclass correlation coefficient [ICC] = >0.80 for all conditions).

Conclusions. Individuals with TBI consistently demonstrated greater visual photosensitivity compared with controls. FL and GL light filtering lenses improved light tolerance for both groups. These results highlight visual photosensitivity as a TBI sequela and suggest that these light filtering lenses may serve as effective treatment options.

Keywords: photophobia, Ocular Photosensitivity Analyzer (OPA), visual photosensitivity threshold (VPT), traumatic brain injury (TBI), FL-41

Photophobia, visual photosensitivity, and photoallodynia are terms that refer to an abnormal sensitivity to artificial and/or natural light. Photophobia can occur as part of various ophthalmic and neurologic disorders, including retinal dystrophies, blepharospasm, migraine, and traumatic brain injury (TBI).[1–4] These symptoms may be accompanied by headache and/or blurring of vision with associated signs including eyelid squeezing, involuntary blinking, or tearing with light exposure. Photophobia severity can vary greatly, from mild discomfort to debilitating pain, with severe cases often preventing individuals from performing daily activities.[5]

TBI, with a global incidence ranging from 369 to 790 cases per 100,000 individuals,[6,7] has previously been associated with photophobia.[8] Studies have found that photophobia is present in over 50% of mild TBI cases within 6 months of injury and despite improvement in the majority of cases, more than 10% of cases experience photophobia symptoms that persist for over a year.[5,9] Unfortunately, there are limited options for the treatment of photophobia, with one treatment option being tinted lenses. Whereas sunglasses may be used outdoors, some studies suggest that prolonged indoor use may lead to dark adaptation of the retina, which may paradoxically increase pain and light

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sensitivity.[10] Thus, alternative tinted lenses have been investigated for their ability to selectively filter out specific wavelengths of light without triggering dark adaptation in the retina. Light filtering can be achieved through a variety of optical techniques, but a common implementation in tinted lenses is through organic dyes that absorb specific wavelengths of light.

The first study to evaluate FL-41 tinted lenses, conducted by Wilkins et al., found that this tint reduced luminance by approximately 50%.[11] In case reports, individuals with migraine, agoraphobia, photosensitive epilepsy, post-traumatic light sensitivity (cerebral asthenopia), and reading difficulties reported symptomatic relief while wearing the FL-41 tinted lenses.[11] In a study of 24 individuals with blepharospasm and photophobia, 71% preferred FL-41 tinted lenses (a tint that blocks the shorter light wavelengths) for mitigation of photophobia.[12] However, not all individuals prefer FL-41 tinted lenses. In a study of 392 military personnel with TBI, spectral filters were selected by individual preference of the participants and varied by the wavelengths of the light that were removed (blue, green, and red-yellow).[13] Therefore, it is still not clear which light filtering lenses are most beneficial in individuals with TBI-associated photophobia.

A limitation to optimizing photophobia treatments has been the lack of standardized methodologies to quantify visual photosensitivity, with most studies relying on participant self-report.[1,14,15] To address this gap, we previously developed the Ocular Photosensitivity Analyzer (OPA), a tool that uses synthesized speech and randomization of light stimulus presentation to quantify a visual photosensitivity threshold (VPT).[16] In prior studies, the OPA provided a reliable measure of visual photosensitivity in individuals with disease (achromatopsia) and healthy controls.[17,18] In this study, we evaluate changes in visual photosensitivity with various light filtering lenses in participants with TBI and non-TBI control participants.

Methods

The study was approved by the University of Miami Institutional Review Board. Informed consent was obtained from all participants. Inclusion criteria were adults aged 18 years and able to consent with English as a primary language. Pregnant women, prisoners, minors, adults unable to consent, individuals with an intraocular disease that could confound photophobia, and those with significant cognitive impairment that would preclude a participant's ability to provide informed consent following TBI were excluded. Cognitive impairment was assessed by the study team using the UCSD Brief Assessment of Capacity to Consent (UBACC).[19] No restrictions were placed on the type, timing, or clinical presentation of TBI in this exploratory study; participants were included regardless of the age at which the injury occurred. Data on demographics, comorbidities, medications, and medical and ocular diagnoses were collected from all participants including migraine history by participant self-report in a yes/no format. Visual photosensitivity was assessed using the Visual Light Sensitivity Questionnaire-8 (VLSQ-8). This validated 8-item questionnaire yields total scores from 8 to 40, with higher scores indicating more severe light sensitivity.[16]

Details of the participants' TBI(s) were collected through an adapted questionnaire that asked about details of the injury, including loss of consciousness (LOC), post-traumatic amnesia (memory loss), and duration of confusion or disorientation. TBI severity was determined by patient report according to the 2019 Department of Defense (DoD) Standard Surveillance Case Definition for TBI Adapted for Armed Forces Health Surveillance Branch (AFHSB) use. In brief, overall severity was defined by the most severe duration of LOC, memory loss, or confusion/disorientation. Severe TBI was defined by confusion or disorientation >24 hours, LOC >24 hours, or memory loss >7 days. Moderate TBI was defined by confusion or disorientation >24 hours, LOC >30 minutes but <24 hours, or memory loss >24 hours but <7 days. Mild TBI had one of the following: confusion or disorientation lasting less than 24 hours, LOC >30 minutes but <24 hours, or memory loss <24 hours.[20,21]

Study participants were assessed using the OPA at baseline (visit #1 [V1]) and at least 1 month but less than 4 months apart (visit #2 [V2]). During each of the two study visits, participants underwent four OPA tests with and without light filtering lenses. The experimental conditions were divided as follows: no lenses (NLs), plano lenses (PLs), FL-41 lenses (FLs), and gray light filtering lenses (GLs). NL was always tested first, and the order of the remaining lenses (PL, FL, and GL) was randomized. The custom-made light filtering lenses were mounted on form-fitting wrap-around frames with minimal gaps to maximize the field of view while minimizing the intrusion of peripheral light (Optical Express; Bascom Palmer Eye Institute, Miami, FL, USA).

Spectral transmission of all tested lenses (PL, FL, and GL) was performed using a spectrometer (Brain Power Inc., Miami, FL, USA) across the visible spectrum (400–700 nm; Fig. 1). PL exhibited a relatively flat transmission profile across the visible region and FL showed a characteristic light transmission profile consistent with other studies.[11,22] The FLs and GLs reduced the light transmittance by approximately 40% across the visible spectra. Benchtop spectral testing of the OPA LED light source alone and the three tested lenses (PL, FL, and GL) was also performed to characterize the effect of the lenses in front of the OPA LED light source using a spectrometer (StellarNet Inc., Tampa, FL, USA; see Fig. 1).

OPA testing was performed to determine the VPT.[18] In brief, room lighting was adjusted to 4 lux and participants underwent a 10-minute adaptation period. Testing was performed without pupil dilatation and participants were asked to remove any lenses. Participants were positioned on the head-chin rest and were instructed to maintain fixation on the single blinking white LED at the cupola center. Automated OPA testing presented light stimuli of varying intensities ranging from 1 to 32,000 lux (0 to 4.5 log lux) and participants indicated whether the light stimulus was uncomfortable by pressing a button. The VPT was calculated from the mean of 10 response reversals. Catch trials, repeated stimuli interspersed at regular intervals, were implemented to generate positive/negative inconsistency scores of the participants' responses. Positive inconsistency signifies a response shift from discomfort (positive) to no discomfort (negative), whereas a negative inconsistency is the reverse. Lower VPTs demonstrate increased light sensitivity (decreased light tolerance), whereas higher VPTs demonstrate decreased light sensitivity (increased light tolerance).

Statistical analysis was performed using Statistical Package for Social Sciences (SPSS) version 28 software (IBM Corporation, Armonk, NY, USA). Chi-square and independent *t*-tests were used to examine differences between the

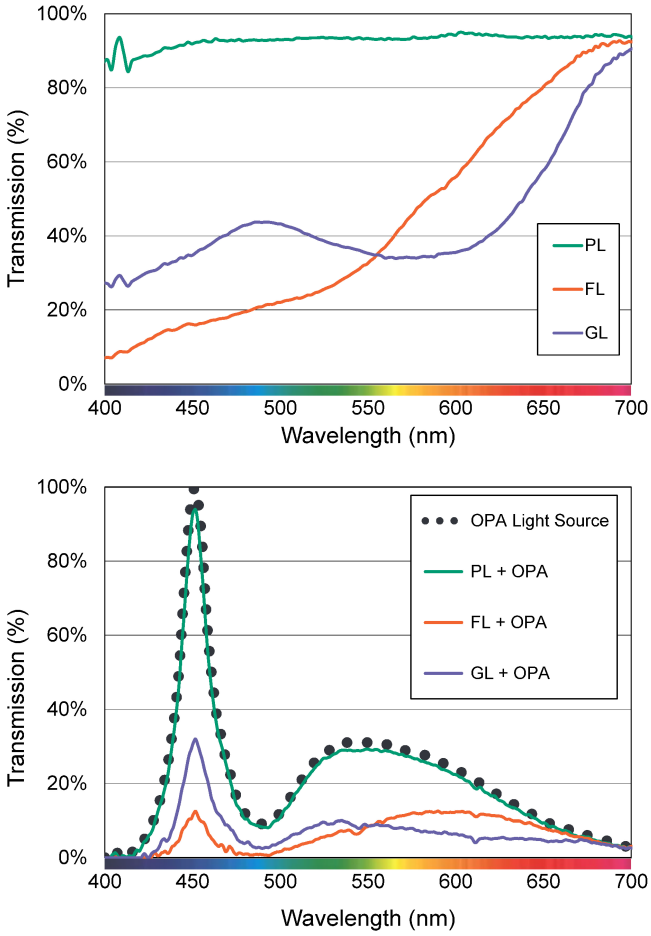

Figure 1. Transmission spectra of the light filtering lenses (PL, FL, and GL) alone (*top*), and combined with the OPA (*bottom*), across the visible spectrum (400 to 700 nm).

TBI and non-TBI control groups. The OPA test-retest reproducibility for VPT measured at each visit was analyzed by reliability analysis. An Intraclass Correlation Coefficient (ICC) between 0.75 and 0.90 indicates good reliability and ≥0.90 was considered to indicate excellent reliability. A repeated measures ANOVA analyzed catch trial agreement, exploring within light filtering conditions and between-group differences. Within-subject comparisons were also conducted to evaluate differences in VPT between PL and each of the other lens conditions at both visits. Paired-samples *t*-tests were performed for each comparison and effect sizes were calculated as Cohen's d.

To determine the VPT individual response stratification to the different filter conditions, we subtracted the PL VPT from either the FL VPT or GL VPT (lux) which were then transformed logarithmically (log lux). Specifically, a "responder" was defined as any individual who had a difference in VPT (log lux) between FL or GL with PL that was greater than 0. The responders were then classified into "mild," "moderate," or "strong" response categories, based on the magnitude of their response. "Mild" responses were determined as those with a difference less than 2 log lux, "moderate" responses were determined as those with a difference greater than or equal to 2 and less than 3 log lux, and "strong" responses were determined as those with a difference greater than or equal to 3 log lux. Additional sensitivity analyses were conducted via ANOVA testing to assess VPT across TBI severity (non-TBI, mild/moderate TBI, and severe TBI). Multivariable models examining patient response to FLs and GLs were also built.

Results

Study Population

Forty-six TBI participants (11 women and 35 men, age = 42.0 ± 15.0 years) and 46 non-TBI control participants (26 women and 20 men, age = 32.5 ± 13.4 years) were included in the study. Of the 92 participants, 88 completed both visits whereas 4 (TBI, $n = 3$ and non-TBI control, $n = 1$) participants were lost to follow-up and unable to complete V2. TBI participants were older, more likely to be men, more likely to have dry eye, more likely to have migraine, and more likely to have self-reported visual photosensitivity than non-TBI control participants (Table 1). TBI participants also had higher VLSQ-8 scores compared with those of non-TBI participants (21.1 ± 8.3 vs. 11.5 ± 3.4, $P < 0.001$). VLSQ-8 scores also strongly correlated with VPT under all lens conditions ($r = -0.6$, $P < 0.001$ for all). Characteristics of TBI were also classified (Table 2).

VPT in the TBI and Non-TBI Control Groups in the NL Condition

The mean measured VPT in the TBI participants in the NL condition was 1.8 ± 0.9 log lux at V1 and 1.4 ± 0.8 log lux at V2 (Fig. 2). The test-retest reproducibility for TBI participants measured during the two in-person visits had good reliability (ICC = 0.81). The mean measured VPT in the non-TBI control participants in the NL condition was 2.6 ± 0.8 log lux at V1 and 2.3 ± 0.8 log lux at V2 (see Fig. 2). The test-retest reproducibility for non-TBI control participants measured during the two in-person visits had good reliability (ICC = 0.87). Comparing the two groups, TBI cases had significantly lower VPTs compared with non-TBI controls (all values $P < 0.01$), indicating higher light sensitivity (Table 3).

VPT in the TBI and Non-TBI Control Groups With Light Filtering Lenses

Similar to the NL conditions, the TBI group had lower VPT values compared to that of non-TBI control participants for all lens conditions ($P < 0.05$). In both groups, the VPT was higher (less sensitivity, higher light tolerance) when using the FL and GL lenses, compared with all other lenses. VPT ICCs were good for all conditions across both groups (Table 3).

VPT by TBI Severity

In the PL condition, non-TBI participants consistently demonstrated higher VPTs compared with both mild/moderate and severe TBI groups. At V1, mean VPTs were 2.5 ± 0.9 log lux in non-TBI controls, 1.4 ± 0.9 log lux in mild/moderate TBI, and 1.4 ± 0.9 log lux in severe TBI. ANOVA testing indicated a significant overall effect ($P < 0.001$). Pairwise comparisons showed that non-TBI VPTs were significantly higher than both mild/moderate ($P < 0.001$) and severe TBI ($P < 0.001$), whereas mild/moderate and severe TBI did not differ ($P = 0.870$). At V2, mean PL

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Table 1. Characteristics of the Study Population

Demographics	TBI (n = 46)	Non-TBI Control (n = 46)	P Value
Age, mean ± SD	42.0 ± 15.0	32.5 ± 13.4	P = 0.002
Sex, n (%)			P = 0.001
F	11 (24)	26 (57)	
M	35 (76)	20 (44)	
Race, n (%)			P = 0.006
White/Caucasian	31 (67)	27 (59)	
Black/African American	10 (22)	3 (7)	
Asian	0 (0)	11 (24)	
Native Hawaiian/Other Pacific Islander	0 (0)	1 (2)	
Other/multiracial	4 (9)	3 (7)	
Prefer not to answer	1 (2)	1 (2)	
Ethnicity, n (%)			P = 0.360
Non-Hispanic	28 (61)	29 (63)	
Hispanic	16 (35)	17 (37)	
Unknown	2 (4)	0 (0)	
Dry eye, n (%)			P = 0.018
Yes	17 (37)	7 (15)	
No	29 (63)	39 (85)	
Migraine, n (%)			P < 0.001
Yes	23 (50)	7 (15)	
No	23 (50)	39 (85)	
Visual photosensitivity, n (%)			P < 0.001
Yes	22 (48)	0 (0)	
No	24 (52)	46 (100)	
Frequency of wearing dark glasses on cloudy days, n (%)			P < 0.001
Never	24 (52)	42 (91)	
Rarely	5 (11)	2 (4)	
Sometimes	6 (13)	2 (4)	
Often	7 (15)	0 (0)	
Always	4 (9)	0 (0)	
VLSQ-8 score, mean ± SD	21.1 ± 8.3	11.5 ± 3.4	P < 0.001

n, number in group; SD, standard deviation; VLSQ-8, Visual Light Sensitivity Questionnaire-8.

VPTs were 2.4 ± 0.8 log lux in non-TBI controls, 1.5 ± 0.7 log lux in mild/moderate TBI, and 1.4 ± 0.9 log lux in severe TBI. ANOVA again demonstrated a significant group effect (P < 0.001). Pairwise tests confirmed that non-TBI participants had significantly higher VPTs compared with mild/moderate (P < 0.001) and severe TBI (P < 0.001), whereas no difference was observed between the TBI subgroups (P = 0.610).

Catch Trial Accuracy

There was no significant difference in overall catch trial accuracy among groups (P = 0.30), or among the four light filtering conditions (P = 0.09; see Table 3). Participant response consistency remained stable as shown by no statistically significant variations in catch trial accuracy across groups and conditions. These results approximate those seen in other forms of visual stimulus testing and demonstrate that participants were responding appropriately to the OPA.[23]

Interindividual Analyses

When comparing PLs with other conditions within participants, consistent patterns emerged across both TBI and non-TBI subgroups (Supplementary Table S1). Among TBI participants, VPTs with FLs and GLs were significantly higher than with PLs at both visits (all P < 0.001), with large within-subject effect sizes (Cohen's d = −0.71 to −0.97 at V1 and −0.71 to −0.87 at V2). NLs showed a small reduction in VPT relative to PLs at V1 (mean difference = −0.2 log lux, P = 0.038), and this effect was absent at V2. Among non-TBI participants, the pattern was nearly identical: VPTs with FLs and GLs were consistently higher than with PLs across both visits (all P < 0.001, effect sizes as large as Cohen's d = −1.54 for GLs at V1 and −1.57 at V2). No significant differences were observed between the PL and NL groups.

Multivariable Models as a Means of Predicting VPT

Four multivariable linear regression models were created predicting VPT (log lux) for each of the conditions (NL, PL, FL, and GL) from the following predictors while controlling for demographics (age, race, ethnicity, and sex) among TBI participants: severity, type, age of incident, years since incident, recency, LOC, time LOC, dazed/confused/disoriented, time disoriented, memory loss, time of memory loss, greater than one TBI, dry eye, migraine, and visual photosensitivity self-report. No significant predictors were found for the NL or PL condition. For FL, the model explained 77.6% of VPT variance (R^2 = 0.776). In this model, the influential factors included age in which VPT decreased by 0.1 log lux for each year (95% confidence interval [CI] = −0.2 to −0.02, P = 0.024), age in which the incident occurred in which VPT increased by 0.1 log lux for each year (95% CI = 0.01–0.2, P = 0.03), years since the incident in which VPT increased by 0.1 log lux for each year (95% CI = 0.02–0.2, P = 0.024), and frequency of dark glasses being worn on

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Table 2. Characteristics of the TBI Population ($n = 46$)

Severity, *n* (%)	
Mild	14 (30)
Moderate	4 (9)
Severe	20 (44)
Undefined	8 (17)
Type, *n* (%)	
MVC	10 (22)
Sports	10 (22)
Pedestrian MVC	3 (7)
Blast	4 (9)
Fall	7 (15)
Other	6 (13)
Unknown	6 (13)
Time, mean ± SD	
Age of incident	24.4 ± 12.7
Years since incident	17.8 ± 16.4
Recency, *n* (%)	
<1 y	3 (7)
1–5 y	7 (15)
6–10 y	11 (24)
11–30 y	13 (28)
>30 y	9 (20)
Unknown	3 (6.5)
Greater than one TBI, *n* (%)	
Yes	7 (15)
No	39 (85)
LOC, *n* (%)	
Yes	29 (63)
No	9 (20)
Unknown	8 (17)
Time LOC, *n* (%)	
<30 min	14 (30)
30 min – 1 h	3 (7)
>24 h	11 (24)
Unknown	9 (20)
Not applicable	9 (20)
Dazed, confused, disoriented, *n* (%)	
Yes	26 (57)
No	3 (7)
Unknown	17 (37)
Time disoriented, *n* (%)	
<24 h	16 (35)
>24 h	10 (22)
Unknown	17 (37)
Not applicable	3 (7)
Memory loss, *n* (%)	
Yes	21 (46)
No	13 (28)
Unknown	12 (26)
Time of memory loss, *n* (%)	
<24 h	3 (7)
>7 d	18 (39)
Unknown	12 (26)
Not applicable	13 (28)

LOC, loss of consciousness; MVC, motor vehicle crash; *n*, number in group; SD, standard deviation.

cloudy days or indoors in which VPT decreased by 0.4 log lux (95% CI = −0.6 to −0.1, $P = 0.006$). Finally, for GLs, the model explained 72.9% of VPT variance ($R^2 = 0.729$). In this model, the influential factors included age in which VPT decreased by 0.1 log lux for each year (95% CI = −0.2 to −0.01, $P = 0.033$) and years since the incident in which VPT increased by 0.1 log lux for each year (95% CI = 0.002–0.2, $P = 0.047$).

Multivariable Models as a Means of Predicting Magnitude of Response to FLs and GLs

Given that, in this study, it was found that the VPTs of FL and GL conditions were significantly greater than the PL condition, further analysis was performed to assess the number of responders to the FLs and GLs and the stratification of the magnitude of response for V1 (Table 4, Supplementary Table S2) from the following variables: TBI severity, TBI type, age of incident, years since incident, dry eye, migraine, photosensitivity, and VLSQ-8 total. For FLs, among non-TBI participants, no covariates were significant. Among TBI participants, race (White/Caucasian as reference) was associated with higher odds of a stronger FL response (odds ratio [OR] = 2.4, 95% CI = 1.1–5.8, $P = 0.037$). For GLs, in non-TBI participants, race (White/Caucasian as reference) was associated with higher odds of a stronger response (OR = 1.9, 95% CI = 1.1–3.5, $P = 0.026$). In TBI participants, ethnicity (non-Hispanic as reference) predicted lower odds of a stronger response to GLs (OR = 0.4, 95% CI = 0.2–0.8, $P = 0.007$).

Discussion

Our study findings suggest that the OPA can reliably measure visual photosensitivity in individuals with TBI, as noted by measurement stability between visits at intervals of between 1 and 4 months. Furthermore, we found that individuals with TBI had greater visual photosensitivity when compared with non-TBI controls, demonstrated by significantly lower VPTs across all conditions. Importantly, VPTs in both groups increased with the use of FLs and GLs, but not with the NL or PL conditions. Our findings are meaningful, as mean VPT increased by at least two log lux while wearing the FLs and GLs as compared to PLs in both TBI and non-TBI control participants. However, individual responses to lens wear varied widely, and neither demographic factors nor TBI characteristics were found to predict the magnitude of improvement in TBI or non-TBI control participants. Taken together, the findings show the potential benefits of FLs and GLs for managing visual photosensitivity in TBI and suggest a personalized approach to treatment.

This study aligns with prior reports using the OPA technology, where participants with TBI had significantly lower VPTs as compared with those without a history of TBI when assessed with the OPA (TBI = 233 and no-TBI = 162, $P < 0.001$).[18,24] Other devices have also been used to quantify VPT in the TBI population with similar findings. One device that used halogen lamps with a maximum light intensity of 16,450 lux (4.2 log lux) found that individuals with persistent post-traumatic headache had a lower mean VPT compared with controls (1.5 log lux, $n = 30$ vs. 2.6 log lux, $n = 35$, $P < 0.05$).[25] Similar findings were noted using a device that presented 40 different stimuli through a tungsten-halogen lamp at random for 4 seconds with intensity ranging from 440 to 1500 lux (2.6 to 3.2 log lux). In this study, 11 individuals with TBI and post-concussive syndrome (PCS) ≥6 months after injury were compared with 11 individuals with TBI but without PCS and 11 controls.[26] Seven individuals in the PCS group, but none in the TBI without PCS or control groups, had severely reduced tolerance at the highest lux

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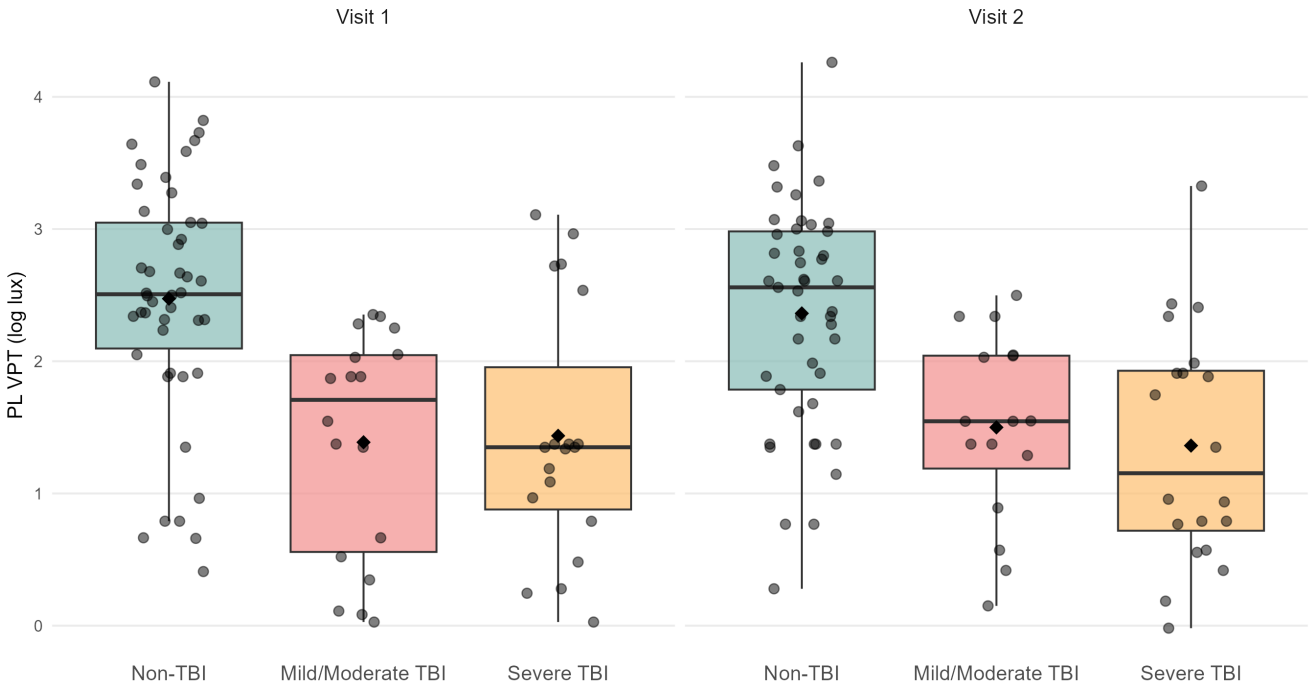

Figure 2. VPT under the PL condition between TBI and non-TBI participants in both visits stratified by TBI severity. Means are indicated by the *black points*, and standard deviations are indicated by the *black horizontal lines*. PL, plano lens; TBI, traumatic brain injury; VPT, visual photosensitivity threshold.

Table 3. VPT by Study Population Who Underwent OPA Testing

Study Population	Light Filtering Condition	Visit #	VPT, log Lux Mean ± STD	Catch Trial Accuracy	Positive Response Inconsistencies	Negative Response Inconsistencies	VPT ICC
TBI	NL	1	1.8 ± 0.9	74.4 ± 14.5%	14.9 ± 15.8%	10.8 ± 13.2%	0.81
		2	1.4 ± 0.8	76.6 ± 18.2%	15.7 ± 14.8%	7.8 ± 9.9%	
	PL	1	1.6 ± 0.9	81.1 ± 15.7%	12.6 ± 13.5%	6.3 ± 9.8%	0.92
		2	1.5 ± 0.9	85.3 ± 15.6%	9.2 ± 13.0%	5.7 ± 11.4%	
	FL	1	1.9 ± 0.9	82.4 ± 12.5%	12.7 ± 11.7%	5.0 ± 9.2%	0.91
		2	1.8 ± 0.9	85.9 ± 16.7%	9.1 ± 13.8%	5.1 ± 8.6%	
	GL	1	1.9 ± 1.0	80.3 ± 18.9%	13.5 ± 14.9%	6.3 ± 11.7%	0.91
		2	1.8 ± 1.0	80.3 ± 17.0%	14.3 ± 15.4%	5.6 ± 9.0%	
Non-TBI control	NL	1	2.6 ± 0.8	80.1 ± 15.1%	10.2 ± 10.4%	9.7 ± 11.2%	0.87
		2	2.3 ± 0.8	83.4 ± 15.7%	10.9 ± 13.1%	5.8 ± 9.6%	
	PL	1	2.5 ± 0.9	84.6 ± 13.1%	9.8 ± 10.4%	5.6 ± 7.8%	0.88
		2	2.4 ± 0.8	78.5 ± 18.2%	14.6 ± 15.3%	7.0 ± 10.7%	
	FL	1	2.8 ± 0.9	81.1 ± 12.3%	13.3 ± 10.6%	5.7 ± 7.4%	0.88
		2	2.7 ± 0.8	81.5 ± 16.0%	11.3 ± 13.4%	7.3 ± 8.9%	
	GL	1	2.8 ± 0.9	79.1 ± 14.3%	14.9 ± 13.3%	6.2 ± 11.1%	0.89
		2	2.7 ± 0.8	80.8 ± 12.6%	13.7 ± 11.2%	5.6 ± 8.3%	

FL, FL-41 lens; GL, gray light filtering lens; ICC, Intraclass Correlation Coefficient; NL, no lens; PL, plano lens; STD, standard deviation; TBI, traumatic brain injury; VPT, visual photosensitivity threshold.

ICC <0.50 indicates poor reliability, 0.50 to 0.75 indicates moderate reliability, 0.75 to 0.90 indicates good reliability, and ≥0.90 signifies excellent reliability.

rating, as determined by participant ratings on a 7-point Likert scale. Despite variation in methodology in the studies described above, the magnitude and range of VPTs for TBI and non-TBI controls is similar to that found in our current study. These data highlight that, as a group, individuals with TBI have higher light sensitivity than controls and that instruments that quantify visual photosensitivity can be used reliably in this population.

Our study highlights that FLs and GLs light filtering lenses increased light tolerance, as seen in other studies. In a crossover study, 30 individuals with blepharospasm were randomized to FL-41 or gray-tinted lenses for 2 weeks, followed by a 2-week washout period, followed by a 2-week period of wearing the other tinted lenses. Questionnaires regarding photophobia and light sensitivity were administered before and after each lens (6-point Likert scale).[22]

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Table 4. VPT Response Stratification in FL and GL

Response Status, *n* (%)	TBI (*n* = 46) FL–PL	Non-TBI Control (*n* = 46) FL–PL	TBI (*n* = 46) GL–PL	Non-TBI Control (*n* = 46) GL–PL
Visit #1				
No response, <0 log lux difference	14 (30)	6 (13)	10 (22)	4 (9)
Mild response, 0–2 log lux difference	19 (41)	12 (26)	20 (44)	10 (22)
Moderate response, 2–3 log lux difference	11 (24)	17 (37)	11 (24)	21 (46)
Strong response, ≥3 log lux difference	2 (4)	11 (24)	5 (11)	11 (24)
Visit #2				
Response Status, *n* (%)	**TBI (*n* = 42) FL–PL**	**Non-TBI Control (*n* = 45) FL–PL**	**TBI (*n* = 42) GL–PL**	**Non-TBI Control (*n* = 45) GL–PL**
No response, <0 log lux difference	6 (14)	4 (9)	10 (24)	1 (2)
Mild response, 0–2 log lux difference	24 (57)	13 (29)	20 (48)	12 (27)
Moderate response, 2–3 log lux difference	11 (26)	15 (33)	10 (24)	20 (44)
Strong response, ≥3 log lux difference	1 (2)	13 (29)	2 (5)	12 (27)

FL–PL, difference between FL-41 lens and plano lens; GL–PL, difference between gray lens and plano lens; *n*, number in group.

Overall, individuals experienced improvement with both lenses, but more so with the FLs (FL = 2.83 vs. gray lens = 1.87, $P = 0.006$). The FL efficacy has also been examined in migraine. One study used a 480 nm optical notch filter (similar to FL-41 filters) as the treatment and a 620 nm filter as a sham. Similar to the blepharospasm study design, 37 individuals with migraine used both notch filters for 2 weeks with a washout period in between.[27] Interestingly, headache scores (HIT-6) were significantly improved with both filters (treatment effect 620 nm vs. 480 nm: −1.26, = 0.20). There was no clear preference for the FL, despite achieving a therapeutic effect. These data suggest that tinted lenses that filter out specific wavelengths can improve light tolerance across several conditions, including TBI.

The neural mechanisms of the light sensitivity in individuals with chronic ocular pain (COP) have been shown using functional magnetic resonance imaging (fMRI). In a prior study, 25 individuals with COP underwent two fMRI scans while looking at a white screen, one session with and one without FL-41 tinted lenses.[28] Nineteen of 25 individuals self-reported decreased light-evoked unpleasantness ratings while wearing FLs. As a group, FL-41 tinted lenses decreased light-evoked responses in the bilateral S1, S2, insular, right temporal pole, precuneus, ACC, and paracingulate cortices, suggesting that FL-41 tinted lenses impact brain structures involved in sensory and affective processing of pain.

Several pathways of visual light sensitivity have been postulated, including a pathway whose origin is intrinsically photosensitive retinal ganglion cells (ipRGCs) in the retina. Containing melanopsin, these cells have the greatest light-evoked potentials when stimulated by blue light, with a peak wavelength sensitivity of 479 nm in humans.[29] In mice, the pathway of ipRGCs from retina to cortex has been mapped through a chain of synapses to exert a parasympathetic vasodilatory response on ocular blood vessels. This subsequently sends nociceptive signals through the trigeminothalamic pathway inducing visual photosensitivity through the trigeminal nociceptive pathway.[30] Given that FL-41 and gray lenses filter out most of the middle spectrum of visible light, including the 480 nm wavelength, this theory also helps to explain the results seen across literature and in this study. A randomized trial found that ipRGC-targeting lenses reduced migraine pain more effectively than control lenses, with greater pain score improvements at 2 hours ($P = 0.021$) and 4 hours ($P = 0.019$), despite similar headache frequency (2.68 vs. 2.63 headaches per participant). Abortive medication use was lower with ipRGC lenses (22% of 98 headaches) compared with controls (35% of 103 headaches), supporting the role of ipRGCs in photosensitivity-related migraine.[31] Animal models have further illustrated why preferentially filtering approximately 480 nm light may be of benefit in TBI; although these studies have specific emphasis on photoallodynia, a painful sensation in response to a typically non-painful light stimulus.[32] TBI-associated photoallodynia most likely occurs secondary to the tissue and cellular reactions following primary blunt mechanical damage. Secondary reactions can include breakdown of the blood-brain barrier, lipid peroxidation, neuroinflammation, and neuronal excitotoxicity, all of which have been described in TBI, and may lead to hypersensitivity within the trigeminal sensory system.[33–35]

Limitations of this study include demographic matching between groups and the potential influence of unmeasured comorbidities, such as diet and sleep, which may have affected the findings. The timing of TBI was also heterogeneous, with some injuries occurring during childhood. This reflects the exploratory design, which placed no restrictions on TBI type, timing, or clinical presentation in order to capture a broad spectrum of disease but may limit more direct comparisons across participants. Migraine history was assessed by participant self-report in a yes/no format without distinction between timing of diagnoses or post-traumatic migraine, limiting the migraine characterization in this cohort. In addition, the Glasgow Coma Scale is a validated measure of TBI severity but was not collected in this study, potentially limiting injury severity stratification in this cohort.

In addition, qualitative patient-reported outcomes assessing perceived comfort or functional benefit with each lens condition were not collected. Although visual photosensitivity thresholds were quantified, future studies should integrate validated subjective measures to better capture clinically meaningful improvements in patients with TBI. The majority of participants with TBI were also more than 6 years removed from their injury, and chronic TBI populations may differ in pathophysiology and symptoms compared with individuals in the acute or subacute post-injury phases. Consequently, the findings may not fully reflect visual photo-

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sensitivity experiences closer to the time of injury, and future work should evaluate whether these relationships are consistent across different post-injury intervals.

Despite these limitations, the study advances understanding of visual photosensitivity in individuals with TBI and identifies FL and GL light-filtering lenses as potential therapies. Further research is warranted to examine additional spectral properties and light transmittance characteristics of lenses for the treatment of visual photosensitivity in this population.

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