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Critical flicker frequency and related symptoms in mild traumatic brain injury

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Abstract

Primary objective: To determine whether critical flicker frequency (CFF) thresholds are abnormal in individuals with mild traumatic brain injury (TBI) and, if so, if they are correlated with the degree of reported motion and light sensitivity.

Methods and procedures: The foveal CFF threshold was assessed in individuals with mild TBI ($n = 18$) having varying degrees of reported light and motion sensitivity. Mean CFF values were obtained using the ascending and descending psychophysical method of limits with binocular viewing at 40 cm. A 7-item, rating-scale questionnaire was used to assess the degree of light and motion sensitivity. These parameters were also assessed in a large visually-normal, non-TBI cohort.

Main outcomes and results: CFF in the mild TBI group was not significantly different across age groups from the visually-normal, non-TBI cohort. However, mean CFF among the mild TBI subjects was significantly higher for the 'light sensitive' and 'motion sensitive' sub-groups when compared to the 'not light sensitive' and 'not motion sensitive' sub-groups. The majority of TBI subjects manifested both light and motion sensitivity.

Conclusion: CFF was found to be related to the reported degree of light and motion sensitivity in individuals with mild TBI. Neurological disinhibition as a result of brain injury may be causal of the subjective hypersensitivity to light and motion in the presence of normal CFF.

Keywords: *Traumatic brain injury, mild brain injury, critical flicker frequency, light sensitivity, motion sensitivity, temporal processing*

Introduction

Critical flicker fusion frequency (CFF) is defined as the lowest frequency at which a physically flickering light is perceived to be non-flickering or 'steady' [1]. CFF is a rapid and simple technique for providing information about the temporal responsivity of the visual system by defining the upper limits of one's temporal resolution. It has been found to vary with various aspects of the stimulus quality and population tested [2–6]. CFF is important not only in assessing the integrity of the retina, but also in ascertaining temporal processing beyond the retina [7–12]. It reflects the capabilities of temporal processing with respect to the speed and transmission aspects of the neural response.

Among traumatic brain-injured (TBI) individuals, many present with a range of visual and neurological impairments [13, 14]. Most relevant symptoms include reports of sensitivity to light and sensitivity to visual motion [15–17]. In such cases, these individuals also reported general visual discomfort and an inability to read efficiently under normal lighting conditions, to view computer screens for prolonged periods of time, to watch television in a darkened room, to function in busy supermarkets or office buildings or even to go outdoors on sunny days. This may be due to the overall variation

(A)

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in illumination level and/or flicker of the lighting conditions. For example, there are frequent complaints from this population that fluorescent lighting is especially bothersome (i.e. flickering effect) and often times causes them extreme visual discomfort inside offices, supermarkets or hospitals that are typically illuminated in this manner [18]. Under normal conditions, the flickering of fluorescent lights is above the human flicker threshold [6, 12]. However, if TBI patients have an abnormal CFF threshold, normal fluorescent lighting and its related apparent flicker and motion may cause significant visual and general discomfort in these patients. Therefore, an abnormality in temporal processing of TBI patients may be related to some of their symptoms.

Thus, the purpose of the present study was to determine the foveal CFF threshold in mild TBI patients and relate this to their reported sensitivity to light and visual motion. If the CFF threshold is different from the normal population, then this would provide insight into the neurological effects of TBI on the temporal visual processing of light and/or motion.

Methods

Subjects

Fifty-six faculty, staff and students of the SUNY State College of Optometry served as the visually-normal, non-TBI control group (see Table I). Ages ranged from 22–83 years, with a mean of 45 years and a standard deviation of ±15 years. There were 25 males and 31 females. Only two subjects reported mild light sensitivity, while all others reported neither light nor visual motion sensitivity. None reported history of past or present retinal or neurological disease nor brain injury. All reported to be in good health.

The mild TBI group consisted of 18 subjects recruited from the Raymond J. Greenwald Rehabilitation Center at the SUNY State College of Optometry (see Table I). Subjects were selected through convenience sampling [19]. Ages ranged from 19–72 years, with a mean and standard deviation of 45.7 ± 13.6 years, respectively. There were six males and 12 females. All were tested at least 3 months post-injury, with a range of 3 months to 15 years and a mean of 5.2 years. They received a comprehensive vision examination, including assessment of refractive state, binocular status and ocular health.

Table I. Comparison of normal and TBI groups.

	Normal	TBI
Age range (years)	22–83	19–72
Mean ± 1 SD (years)	45 ± 15	45.7 ± 13.6
Male : female ratio	25 : 31	6:12
Range of time post-injury (years)	—	0.25–15
Mean time post injury (years)	—	5.2

Individuals with glaucoma, cataracts and other retinal or optic nerve disorders were excluded from the study due to the possible effects on CFF [20]. Those with myopia above 8.00 diopters were also excluded, as lower CFF values have been reported in this highly myopic population [21]. Other exclusion criteria included subjects having a history of seizures, vertigo, dizziness or excessive fatigue, which may be exacerbated by the flickering nature of the stimulus.

The study was approved by the SUNY State College of Optometry Institutional Review Board and followed the tenets of the Declaration of Helsinki. All subjects provided written, informed consent.

Apparatus

The foveal CFF was measured using an experimental device developed and fabricated at the college. It consisted of an array of four adjacent white LED's with a spectrum of 460–555 nm (The LED Light Inc, Carson City, NV, theledlight.com) that provided diffuse illumination through a circular piece of translucent white plexiglass 4 cm in diameter (Figure 1a). The device was mounted onto an optical bench and placed 40 cm away along the subject's midline in primary

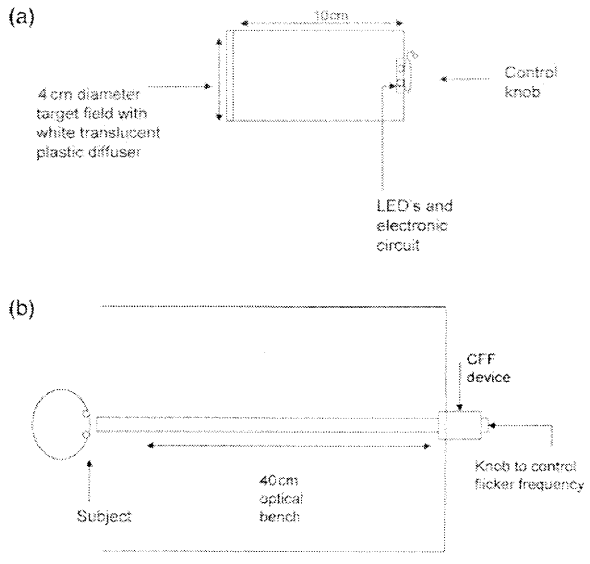


Figure 1. (a) Schematic representation of CFF device (side view). (b) Top view of CFF device and apparatus.

position (Figure 1b). The CFF test device was enclosed within a flat matte black foamboard enclosure to reduce stray illumination, as well as to minimize visual distractions. The right side panel had an opening for the experimenter to view the subject and align the outer canthus of the subject's right eye with the centre of the CFF device, as well as to monitor accuracy of eye fixation. A headrest/chinrest set-up was mounted to the front of the optical bench. The target luminance was 304.4 cd m^{-2}, while background luminance was 0.86 cd m^{-2}. Contrast of the target was 99.9% against the black background. The size of the white test field was 5.7°. A calibrated black knob was mounted on the back of the CFF device, which allowed the researcher to slowly change (~1 Hz s^{-1}) the frequency of the test target flicker rate. The frequency range was 30–60 Hz.

Procedures

Subjects placed their head into the chin and forehead assembly. They were asked to fixate the centre of the test field. The test procedure was conducted binocularly with refractive correction in place. Subjects were instructed to indicate by depressing a hand-held clicker when they first saw the perceptually flickering light stop flickering or appearing 'fused' and then to indicate when the now perceptually non-flickering light again appeared to flicker. Thus, the ascending and descending psychophysical method of limits was used [1]. A demonstration of both a flickering and non-flickering light was provided for the subject followed by several practice trials. Once the subject understood the instructions and a consistent response level was obtained, then 10 ascending and 10 descending measurements were taken, with the direction being counterbalanced across subjects. Mean values for the separate ascending and descending CFF values were calculated and then averaged. Normal subject data were averaged and compiled into 5-year bins (i.e. from 21–25, 26–30, ...). Subjects were allowed as many rest periods as needed during the course of the experiment if fatigued.

Subjects were also administered a 7-item, rating-scale questionnaire (see the Appendix) covering the topics of light and motion sensitivity developed in part by Du et al. [15]. Specifically, individuals were requested to rate the degree of light sensitivity and the degree of visual motion sensitivity on a scale of 1–4: 1 = never, 2 = mild, 3 = moderate or 4 = marked. They were also asked to classify the discomfort associated with their light sensitivity on a scale of 1–5: 1 = no discomfort, 2 = somewhat bothersome, 3 = bothersome with no pain or headaches, 4 = very bothersome with some pain associated and 5 = very bothersome and very painful. The survey also included additional questions regarding the different types of illumination that were most bothersome, as well as questions regarding the onset of their light sensitivity. Lastly, subjects were asked to identify factors that either exacerbated (e.g. fatigue) or reduced (e.g. spectacle lens tints, brimmed hats or eye lid squinting) their light sensitivity.

Results

Foveal CFF as a function of age in the visually-normal, non-TBI control group is presented in Figure 2. The CFF averaged over the entire group was 47.26 Hz (SEM = ±0.43 Hz), with sub-group variability appearing to be independent of age. It ranged from 38.5–53.9 Hz, with a SEM of 0.43 Hz. Despite the lack of a significant difference in CFF with age [$F(3,14) = 0.64$, $p = 0.60$], the lowest mean sub-group CFF and individual CFF values were found in the oldest group (i.e. 66+ years of age).

CFF as a function of age in both the control group and mild TBI group is presented in Figure 3. In the control group, linear regression analysis indicated no significant change with age ($y = -0.013x + 47.84$, $r = -0.059$, $p = 0.67$). Similarly, in the mild TBI group, linear regression analysis showed no significant change with age ($y = 0.146x + 41.97$, $r = 0.44$, $p = 0.067$), although a trend was noted. There was no correlation between CFF and the number of years since the most recent TBI ($r = 0.06$, $p = 0.83$).

Figure 4 presents the overall mean CFF for the visually-normal control group and the mild TBI group. In the control group, the mean CFF was 47.26 Hz (SEM ± 0.43 Hz, SD ± 3.18 Hz). In the TBI group, the mean CFF was 48.65 Hz

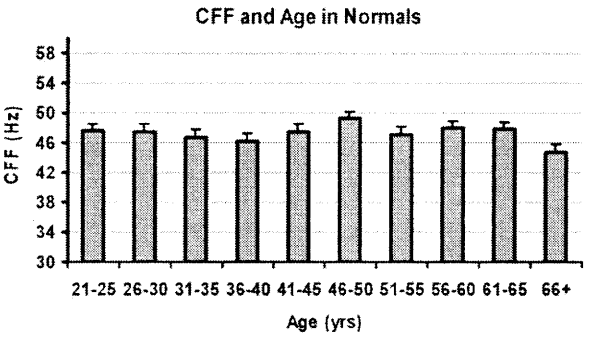


Figure 2. CFF as a function of age in the visually-normal control group. Plotted is the mean CFF + 1 SEM for each 5-year bin. Each bin has 4–7 subjects.

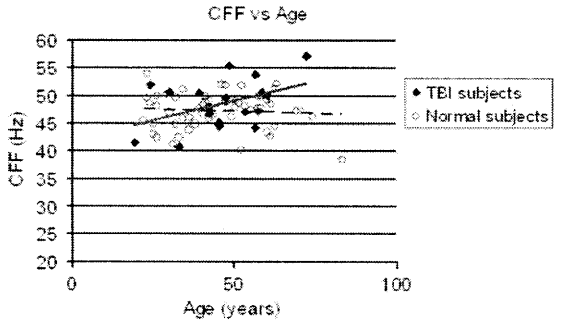


Figure 3. CFF as a function of age in the visually-normal control and TBI group. The dashed line is the linear regression for the control group ($y = -0.013x + 47.84$, $r = -0.059$), and the solid line is the linear regression for the TBI group ($y = 0.146x + 41.97$, $r = 0.44$).

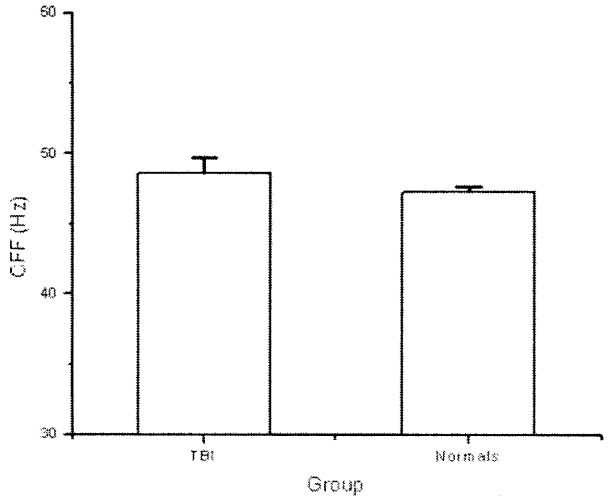
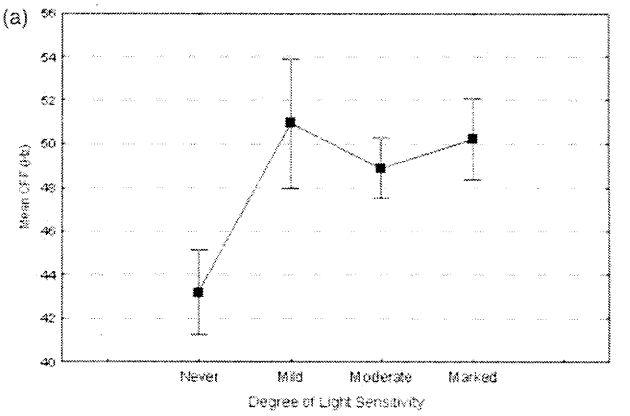


Figure 4. CFF for the visually-normal control group and the TBI group. Plotted is the mean + 1 SEM.



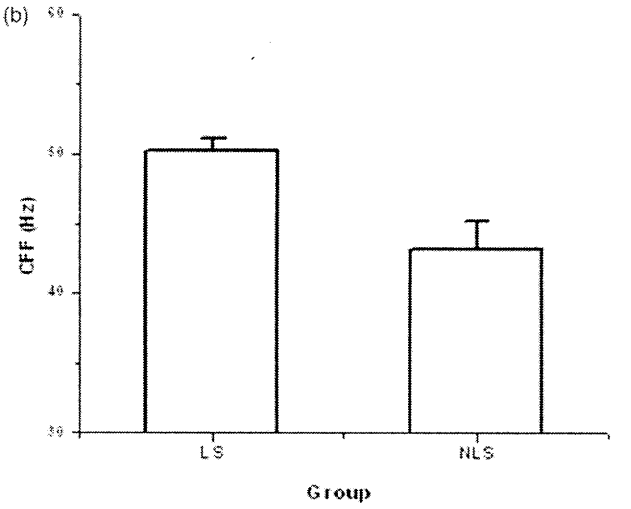


Figure 5. (a) CFF as a function of degree of light sensitivity in the TBI group. Plotted is the mean ± 1 SEM for the four levels of light sensitivity. (b) CFF in the 'light sensitive' vs 'not light sensitive' sub-groups. Plotted is the mean + 1 SEM. Symbols: LS = light sensitive; NLS = not light sensitive.

(SEM ± 1.05 Hz, SD ± 4.52 Hz). These mean differences in CFF were not statistically significant [$t(72) = -1.45$, $p = 0.15$]. However, variability was more than two times greater in the mild TBI group (0.42 Hz vs. 1.05 Hz).

Figure 5(a) presents the mean CFF values in the mild TBI group averaged across all ages as a function of the degree of light sensitivity. There was a trend for CFF to be related to the degree of light sensitivity [$F(3,14) = 3.095$, $p = 0.061$]. Furthermore, when the data were combined into only two sub-groups, namely 'light-sensitive' and 'not light-sensitive', as shown in Figure 5(b), there was a significant effect with regard to the mean CFF threshold [$t = -2.698$, $p = 0.016$]. Of interest, TBI patients who were 'light sensitive' had a significantly higher CFF threshold value than those who were 'not light sensitive'. (E)

Figure 6(a) presents the mean CFF values in the mild TBI group across all ages as a function of the degree of motion sensitivity. There was a trend for CFF to be related to the degree of motion sensitivity [$F(3,14) = 3.129$, $p = 0.060$]. Furthermore, when the data were combined into only two sub-groups, namely 'motion sensitive' and 'not motion sensitive', as shown in Figure 6(b), there was a significant effect with regard to the mean CFF threshold [$t(16) = -2.813$, $p = 0.013$]. TBI patients who were 'motion-sensitive' had significantly higher CFF threshold values than those who were 'not motion sensitive'. (F)

Statistical analysis was performed on key questionnaire responses. In Figure 7(a), CFF threshold was plotted as a function of the severity of symptoms associated with light sensitivity in the mild TBI group according to the responses derived from question #2. One-way ANOVA revealed a significant difference related to CFF and severity of symptoms [$F(3,14) = 3.38$, $p = 0.049$]. The Fisher LSD post-hoc test revealed a significant difference between the 'no symptoms' and 'very bothersome,

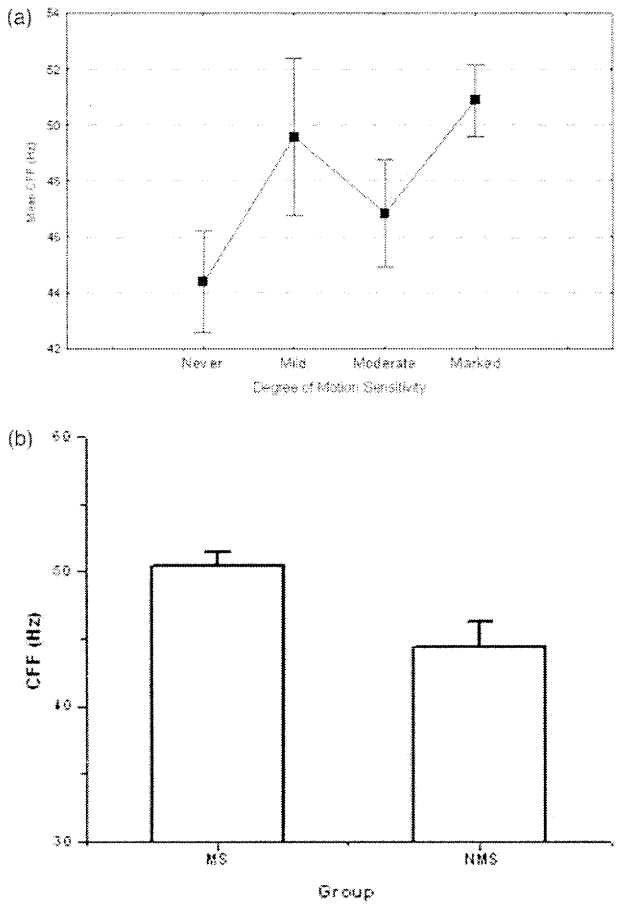


Figure 6. (a) CFF as a function of degree of motion sensitivity in the TBI group. Plotted is the mean ± 1 SEM for the four levels of motion sensitivity. (b) CFF in 'motion sensitive' vs 'not motion sensitive' sub-groups. Plotted is the mean + 1 SEM. Symbols: MS = motion sensitive; NMS = not light sensitive.

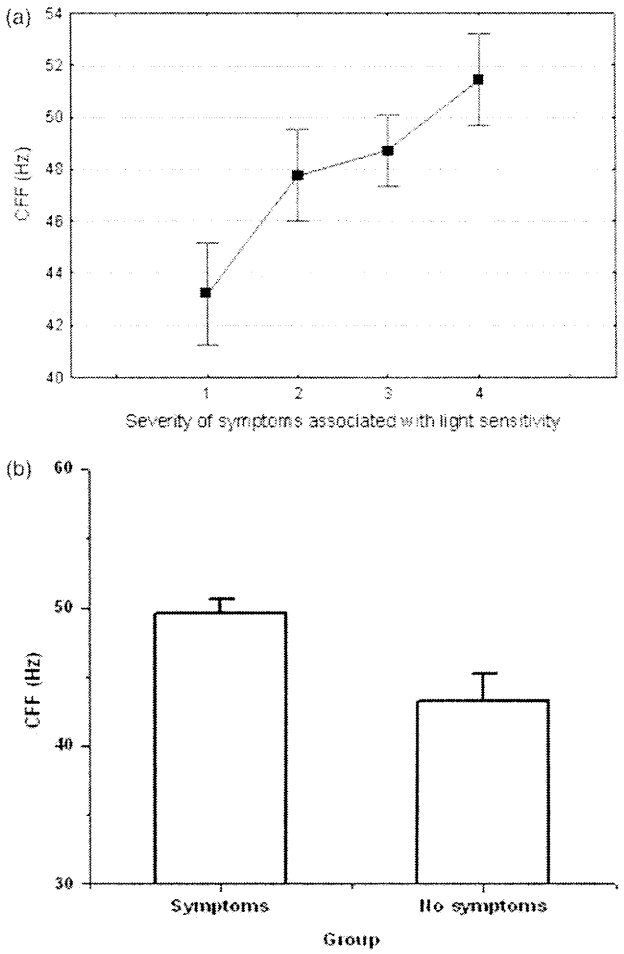


Figure 7. (a) CFF plotted as a function of severity of symptoms associated with light sensitivity in the TBI group. 1 = no symptoms; 2 = somewhat bothersome; 3 = bothersome, no pain, no HA; 4 = very bothersome, some pain. (b) CFF in the 'symptoms' vs 'no symptoms' sub-groups. Plotted is the mean + 1 SEM.

some pain' sub-groups ($p = 0.007$) and a trend between the 'no symptoms' and 'bothersome, no pain no HA' sub-groups ($p = 0.053$). Thus, CFF was higher in the two above symptomatic sub-groups. In Figure 7(b), the subjects were divided into two sub-groups, 'symptoms' and 'no symptoms', revealing a significantly higher CFF in the 'symptoms' sub-group ($t = -2.698$, $p = 0.016$). Due to the categorization used in questions 1 and 2, the same sample of individuals was represented in Figures 7(b) and 5(b).

Discussion

The results of the present study demonstrated that the foveal CFF was not significantly different between the mild TBI group and the visually-normal, non-TBI control group. This is consistent with some of the past studies [22]. However, some individuals with TBI who exhibited photosensitivity had a higher CFF than that found in those without photosensitivity. The results of the present study also revealed that a relatively elevated CFF was present in TBI patients who had both light and motion sensitivity. Furthermore, CFF was found to be significantly elevated in TBI patients who had an increased severity of symptoms as well. This *relative* hypersensitivity to normal illumination conditions [15, 16] is consistent with related findings in the literature, which have reported that individuals with TBI manifest hypersensitivity to normal sounds (i.e. hyperacusis) in the presence of normal auditory sensitivity [23].

Effect of TBI on the neurosensory threshold

Earlier studies suggested that, when brain injury was sustained, there were consequent decreases in overall

neurological function and sensitivity [24–26]. (I) Yet, in many cases of closed-head injuries, the sensation of hypersensitivity has been noted [17, 27]. For example, Du et al. [15] also found that, in photosensitive subjects with mild TBI, there was an elevated threshold for dark adaptation, thus suggesting reduced retinal and neurological sensitivity in selected vision functions, an apparent paradox. However, they too found that dark adaptation thresholds did not differentiate the subjects with TBI from their normal sample, but rather revealed a *relatively* elevated dark adaptation threshold that correlated with the degree of photosensitivity experienced by the TBI subjects. This finding is similar to that of the present study, demonstrating that the overall CFF does not differ between TBI and normal groups, but rather within the light-sensitive and visual motion-sensitive TBI symptomatic sub-groups.

Relation to symptoms

When CFF was compared with the severity of symptoms (Figure 7a), it was found to be higher in the two sub-groups that exhibited the most severe symptoms when compared to the asymptomatic sub-group. These findings suggest that individuals with mild TBI do not exhibit abnormal basic temporal processing abilities *per se* as compared to normal individuals, but rather an inability to tolerate perceptually temporal stimuli that normally would not provoke symptoms. One possibility is that those with TBI also manifesting hypersensitivity to normal temporal stimuli have abnormal neural disinhibition (i.e. reduced normal inhibition) of temporal processing leading to increased gain in sensitivity. This is similar to the phenomenon of hyperacusis experienced by post-TBI subjects despite the presence of normal auditory processing [23, 27]. In such cases, individuals with TBI who initially exhibited higher temporal resolution may not have manifested awareness of light and motion sensitivity symptoms prior to head trauma due to the presence of (J) a normal inhibitory process. However, if sustaining a head injury produces damage to inhibitory processes, while leaving temporal processing pathways intact, individuals with TBI may no longer exhibit normal inhibition of typical temporal stimuli. Thus, this may lead to the experience of excessive light and motion sensitivity. For example, in a study conducted using post-concussional patients, Bohnen et al. [28] found a lowered tolerance to light and sound when compared to a normal age-matched population. They also speculated that the reduced tolerance to normal lighting conditions could be due to disinhibition from the orbital frontal cortex on sensory pathways. In other words, efferent pathways affecting sensory awareness may be involved in producing greater sensitivity to a bright flickering stimulus [29].

Clinical implications

Functionally speaking, common light stimuli, such as normal fluorescent room illumination, may produce symptoms in individuals with mild TBI that are otherwise well-tolerated by a visually-normal, non-TBI cohort. As noted from the present study, eight of the 18 TBI subjects reported sensitivity to fluorescent lighting alone, while the others reported sensitivity either to outdoor lighting or to all forms of lighting. In identifying these factors, simple measures can be taken to reduce these symptoms. Such aids as wide-brimmed hats for outdoor lighting and tints for indoor fluorescent lighting have been suggested to reduce these symptoms experienced by patients after a TBI injury [14]. Clinicians may also advise these patients (K) to replace household fluorescent lighting with incandescent lighting, thereby ameliorating these flicker-based symptoms. This would improve their overall quality of life.

Study limitations

First, the present sample was moderate. A greater (L) number of TBI subjects in each of the symptom categories manifesting a wider range of symptoms may be useful in demonstrating a stronger relationship between the CFF threshold and the severity of symptoms. Secondly, testing was only done at the fovea. Further evaluation should be conducted at additional retinal sites in the near and far retinal periphery to assess the effectiveness of CFF as a measure of brain damage and overall visual field integrity. This would contribute to a better understanding of the pathways affected in this population to produce hyperaesthesia, such as light and motion sensitivity.

Conclusions

The present findings of increased light and motion sensitivity experienced by individuals with TBI despite normal CFF threshold reinforce the subjective impression of annoyance of flickering lights, such as fluorescent lighting and extreme (M) motion in their visual field as might be found in a bright crowded supermarket. This may reflect

a neurological disinhibition phenomenon, thus producing hypersensitivity to visual stimuli in the presence of normal CFF. CFF could aid clinicians by allowing them to use this rapid and easy method to determine severity of a patient's symptoms and furthermore to assess the outcome of prescribed treatments.

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Appendix: Symptom rating-scale questionnaire

(1) Are you sensitive to light? Please rate it from 1–4 as listed below.

(1) never
(2) mild
(3) moderate
(4) marked

(2) Is there any discomfort, headaches or pain associated with the light sensitivity?

(1) no discomfort associated
(2) somewhat bothersome
(3) bothersome, but no pain or headaches associated with it
(4) very bothersome with some pain associated
(5) very bothersome and very painful

(3) What kind of light bothers you the most?

(1) indoor incandescent lighting
(2) outdoor light
(3) fluorescent lighting
(4) all lighting

(4) Did you start experiencing light sensitivity before or after the head trauma?

(1) before the traumatic brain injury
(2) after the traumatic brain injury

(5) What increases the light sensitivity?

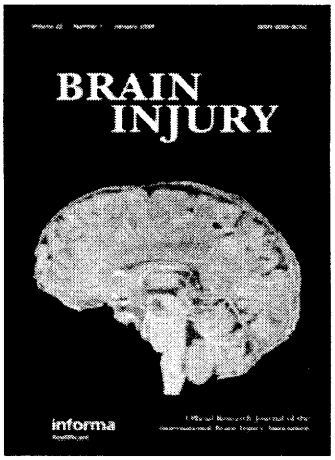
(1) fatigue
(2) time (worsens as the day goes on)
(3) computer use
(4) television and movies
(5) Other (specify) _____

(6) What do you do to reduce the light sensitivity?

(1) tints
(2) don't go out when it's bright
(3) brimmed hat
(4) squint
(5) other (specify) _____

(7) Do you ever experience increased sensitivity to visual motion?

(1) 1 – never
(2) 2 – mild
(3) 3 – moderate
(4) 4 – marked



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Re: **Critical Flicker Frequency and Related Symptoms in Mild Traumatic Brain Injury**
Study by Dept. of Clinical Sciences and Vision Sciences, SUNY

Date: 15 April 2008

From: Gerald J. (Jerry) Straub, 1637 Noah Street, Adrian, MI 49221; Phone: 517-263-0760

Comments and discussion notes

General
This is an excellent presentation of a topic which is of vital interest to many with "mild" TBI and the various issues associated therewith. As a survivor (12+ years post MVA) with total loss of vestibular function, I was unable to walk unaided for the first ten years. Then, with Neuro-Optometric Rehabilitation, at Excel Institute in Traverse City, MI, I learned to replace the vestibular function with visual cues. That was a tremendous success. Along with the resulting improvement in cognitive functioning it restored a sense of self-reliance. I was able to walk without a walking stick!

Then, as described in the attached article, from the 23 December 2007 issue of the Adrian Daily Telegram, my world came crashing down with the advent of Compact Fluorescent Lights.

Compact Fluorescent Lights (CFL's) are a major problem. They disorient me and take away my ability to walk, apparently negating, the hard work and training at Excel. Discussing it with Drs. Perlman and Hansen as well as our two sons (both P.E.'s), we have been unable to ascertain the specific component of the CFL which causes the problem. It could be the flicker of the cycles, some other undefined mechanical property of the light, or possibly even RFI, from the ballast, interfering with brain waves. Our daughter, who is a Speech and Language Pathologist working with children with autism, tells us that these children often have an adverse reaction to fluorescent lighting.

Your study of the effects of Critical Flicker Frequency begins to fill in the knowledge gaps. This will enable us, along with the great team of medical professionals, to sort out this problem and determine if there is any coping strategy, or perhaps the use of the Anifra lenses, which will allow me to regain some sense of independence. With LED bulbs coming soon (see attached article from Forbes Magazine of 23 July 2007), it is possible that free market economics and environmental good sense will effectively eliminate the problematic, mercury-laced CFL's. However, three recent inadvertent violent encounters with CFL's have left me badly shaken. I live with the fear that a fall may further damage my brain stem. This set-back leaves me very discouraged, demoralized, and somewhat angry.

The comments, below, are based upon the life experiences mentioned above. They are intended to elucidate rather than to critique your sterling efforts.

Comments, keyed to the alpha characters in the margin of the study copy attached:

(A) This is a very significant, disabling symptom in TBI survivors with whom I have been associated in several support groups. Based upon my empirical observations that is a sizeable number of people.

(B) This is the phenomenon to which Glen Johnson, Ph.D. refers, in his writings found at tbiguide.com, as "Meijer's Effect".

C) Regular (4' tube) fluorescents cause discomfort and confusion in quite a few cases. However, in my case, exposure to CFL's , even at a distance of 10' to 20', results in instantaneous deterioration and rapid loss of functioning, at both the physical and cognitive levels.

(D) Question: Does this refer to post-injury symptoms? If so, I submit that a large number of TBI survivors are so affected. It would seem to skew the results of this study if they were excluded. However, since my experience is based upon working with and participating in support groups, it is possible that participants in support groups are more likely to exhibit these symptoms than those who have recovered to the extent that they no longer engage in the exchange of ideas/experiences at that level.

(E) Please refer to note (A). A large number of TBI survivors exhibit light sensitivity. One could postulate that support groups are comprised of those with more significant neurological damage.

(F) Again, based upon my experience and observations, it seems that motion sensitivity and light sensitivity are often concurrent. In my situation, with a total loss of vestibular function, Neuro-Optometric Rehabilitation has taught me to rely on visual cues and coping strategies to compensate for the lack of neurological vestibular inputs.

(G) Please refer to notes (A) and (E).

(H) Again, in the world of TBI survivors there is a considerable population of those who exhibit sensitivity to both light and motion.

(I) True, again, in substantial numbers of the TBI population.

(J) Right on!

(K) Absolutely. Particular attention should be paid to the total avoidance of exposure to CFL's. Not only do we not use them in our home, after the incident in December of 2006, but our coping strategies consist of my wife inspecting restaurants and places of public accommodation to assure that I will be safe from that hazard. We are going out of town for our grandson's high school graduation. It required two days of calling hotels to ascertain the CFL situation. We were able to find only two, in Louisville, KY, which did not use CFL's. On a local level, we have been able to find a group of restaurants and fast-food places which are managed/owned by people who have accommodated our need. Your suggestion of the use of glasses with Anifra-tint lenses certainly merits consideration.

(L) An excellent point.

(M) This agrees with my experience as well as with Dr. Glen Johnson's "Meijer's Effect" observation. I have wondered what role the diminished cognitive functioning may play in the ability to process the multiple inputs. I suspect that is, to some extent, a factor.

End notes:
Your study is a truly ambitious piece of work which validates much of the information which many TBI survivors have observed. It also challenges medical practitioners to evaluate their TBI patients in view of these findings. I have been blessed in that Dr. Owen Perlman has put together an "all star" team.

One wonders if the Veteran's Administration has any procedures to screen returning personnel for TBI and/or loss of vestibular functioning. It is possible that many of these wounded heroes could have a substantial improvement in their quality of life by the application of Neuro-Optometric Rehabilitation.

Thank you for the excellent job of defining these issues which are so critical to the proper care and recovery of TBI survivors.

If I can be of any help, please call. Again, thank you so very much.