Central Visual Oscillopsia: Case Report and Review of the Literature

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Abstract: Here we present a patient with persistent central visual oscillopsia, review the literature on this condition, and report results from an experimental intervention using repetitive transcranial magnetic stimulation. A 57-year-old man reported persistent visual oscillopsia after a traumatic brain injury suffered 20 years earlier. Symptoms were presumed to be of cortical origin given his normal eye movements, eye stability, and peripheral vestibular function. Furthermore, he reported oscillopsia with visual imagery during eye closure. Occipital lesions damaging white matter connections identified on magnetic resonance imaging were suspected to be the cause of his symptoms. Repetitive transcranial magnetic stimulation was applied to the left extrastriate visual motion area V5/MT, to bilateral V5/MT, and to bilateral striate visual area V1. The primary outcome measure was dynamic visual acuity. Secondary outcome measures were gaze stabilization testing and subjective improvement as noted by interviews of the patient. Gaze stabilization and dynamic visual acuity testing revealed no difference between pre- and post-intervention with repetitive transcranial magnetic stimulation. The patient reported symptomatic improvement in large-amplitude oscillations that persisted for at least 12 months, but stated that smaller-amplitude oscillations were unchanged. Pathologies associated with central oscillopsia in the literature include neuromyelitis optica spectrum disorder, stroke, migraine without infarction, and psychological trauma. The patient's reported improvement in large- but not small-amplitude oscillopsia suggests that these symptoms may result from different neurophysiological mechanisms. Repetitive transcranial magnetic stimulation did not result in clinically significant improvement, suggesting a need for other strategies to treat this condition.

Key Words: transcranial magnetic stimulation, visual oscillopsia, traumatic brain injury

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DVAT = dynamic visual acuity testing. **GST** = gaze stabilization testing. **MNI** = Montreal Neurological Institute. **PPO** = persistent peripheral oscillopsia. **rTMS** = repetitive transcranial magnetic stimulation. **TBI** = traumatic brain injury. **VOR** = vestibular ocular reflex.

Oscillopsia is a disorder in which objects in a person's visual field appear to move in an oscillating pattern (Tilikete and Vighetto, 2011). The condition is usually caused by abnormal eye stability and eye movements (eg, acquired nystagmus) or hyperactivity in the vestibular or oculomotor system (Aschoff et al, 1974; Grünbauer et al, 1998; Knight et al, 1984). These etiologies are collectively referred to as "peripheral oscillopsia," while "central oscillopsia" refers to oscillopsia caused by cortical dysfunction. Cases of central oscillopsia have been reported, but the condition is much less common than peripheral oscillopsia. In these instances, oscillopsia has been associated with neuromyelitis optica spectrum disorder, stroke due to middle cerebral artery dissection, migraine without infarction, and idiopathic etiologies (Jacome, 2013; Kim et al, 2012; Nunez et al, 2014; Suzuki et al, 2004).

While little is known about how brain lesions cause central oscillopsia, some authors have suggested that positive illusory motion symptoms may be induced by pathologic remodeling of damaged tissue, leading to cortical hyperexcitability and abnormal visual phenomena (Reinecke et al, 2003; Villamar et al, 2012). Hyperexcitability is proposed to be mediated by increased NMDA (*N*-methyl-D-aspartic acid) and AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid) receptor activity, which is associated with an increased sensitivity to glutamate (Park et al, 2008).

Unfortunately, syndromes like central oscillopsia that arise from cortical hyperexcitability are difficult to treat and rarely respond to pharmacologic agents (Moller, 2000). Repetitive transcranial magnetic stimulation (rTMS) is a noninvasive neurostimulation method in which a small handheld coil is placed over the scalp to induce a magnetic field in underlying cortical structures (Kluger and Triggs, 2007). Although the mechanism by which rTMS modulates cortex remains poorly understood, it has been shown to decrease cortical hyperexcitability (Ridding and Rothwell, 2007). Siebner et al (2004) reported a greater than 20-minute reduction in

cortical excitability with 1-Hz rTMS therapy. Thus, rTMS has been used to treat conditions presumed secondary to increased cortical activity, including tinnitus (Anders et al, 2010) and central pain (Leung et al, 2009), with remission of symptoms lasting several months.

Administration of rTMS has also been shown to reduce the perceptual threshold of motion (Silvanto et al, 2008). Since our patient's oscillopsia followed a traumatic brain injury (TBI) and testing did not suggest vestibular dysfunction or eye movement instability, we propose that the pathophysiology of his oscillopsia may be due to hyperexcitability resulting from pathologic remodeling of cortical tissue. Given a presumed etiology of hyperexcitability, we hypothesized that rTMS might provide therapeutic benefit for his visual symptoms.

CASE REPORT

A 57-year-old man had suffered from binocular oscillopsia for more than 20 years following a TBI in December 1996 as a result of a plane crash. The mechanism of the TBI included a hemorrhage and diffuse axonal shearing with visible damage in both frontal and left greater than right occipital white matter (Figure 1). Such damage was expected for the type of deceleration injury he experienced (Villamar et al, 2012). After the TBI, objects in his visual field appeared to oscillate horizontally. The oscillations were not suppressed by eye closure, as he reported that imagined objects also oscillated. He reported that the amplitude and frequency of the oscillations were more pronounced when fixating on a given target and seemed to worsen over the course of the day. While closer objects were easier to focus on, the frequency and amplitude of the oscillations did not change when he viewed objects at a distance. He reported that his oscillopsia made reading small print very difficult. He experienced unsteadiness and a couple of falls after the TBI, and he underwent vestibular rehabilitation with physical therapy without benefit. His other medical, family, and social histories were noncontributory.

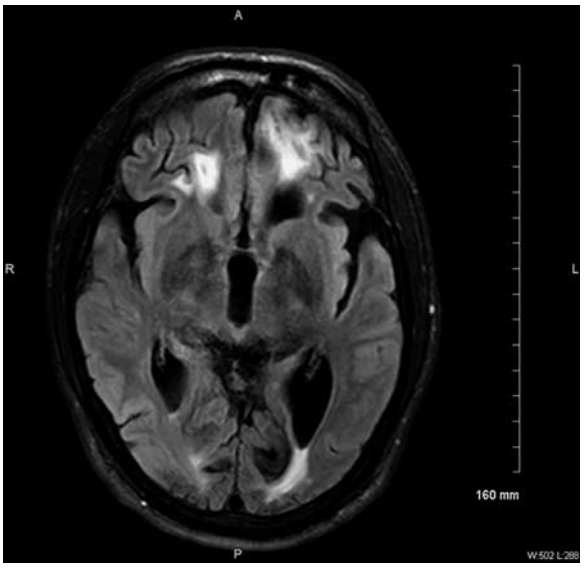

FIGURE 1. T1-weighted magnetic resonance imaging from the patient after injury revealed moderate lateral and mid-third ventricular dilation. Cystic changes, volume loss, and abnormal white matter were observed bilaterally in the frontal lobe. Abnormalities were noted in the left occipital lobe cortices and white matter.

On general neurologic examination, the patient had normal mental status and strength. He had mildly increased tone and slowing of fine motor movements, worse on his left side, and a mildly unstable and wide-based gait. He had no tremor (specifically no head tremor) or other abnormal involuntary movements. He had symmetrical eye movements without nystagmus or abnormal saccades. He had no involuntary, paroxysmal, or otherwise abnormal ocular movements. Fundoscopic examination revealed normal optic nerves. The patient did not demonstrate nystagmus during gaze stability testing, during positional testing, or on bedside Dix-Hallpike testing.

Magnetic resonance imaging after the TBI revealed moderate lateral and mid-third ventricular dilation, and bilateral frontal regions demonstrated cystic changes, volume loss, and abnormal white matter (Figure 1). The occipital lobe cortices had atrophy and white matter damage, which was greater on the left. The cortical area V5/MT did not show visual damage, but a white matter lesion was apparent adjacent to V5/MT.

Vestibular-evoked myogenic potentials were normal, and videonystagmography testing, including saccades, smooth pursuits, gaze stability, optokinetic nystagmus, Dix-Hallpike testing, positional testing, and caloric irrigations, yielded no evidence of vestibular dysfunction. Videonystagmography testing also showed no evidence of central oculomotor abnormality, pathologic nystagmus, or peripheral or central vestibular damage. Visual field testing showed a right lower quadrant deficit bilaterally, which correlates to damage in the left occipital lobe (Figures 2, 3).

Central oscillopsia as the cause of the patient's illusory motion was supported by the lack of evidence for vestibular dysfunction, the persistence of symptoms with eyes closed, and the visual cortex lesions identified on magnetic resonance imaging. Pharmacotherapeutic interventions theorized to target central oscillopsia were attempted and included amantadine hydrochloride 100 mg twice daily, carbamazepine 200 mg three times daily, and methylphenidate 5 mg twice daily (Strupp et al, 2016). Each therapy was administered for a month and then discontinued when no change in symptoms was observed. Treatment periods for these three therapies did not overlap.

INTERVENTION AND OUTCOME MEASURES

This study was approved by the Colorado Multiple Institutional Review Board. The patient provided written consent for the clinical intervention and for publication of the details of his case.

rTMS Intervention

rTMS was delivered with an air-cooled Magstim SuperRapid figure-of-eight coil and Magstim SuperRapid

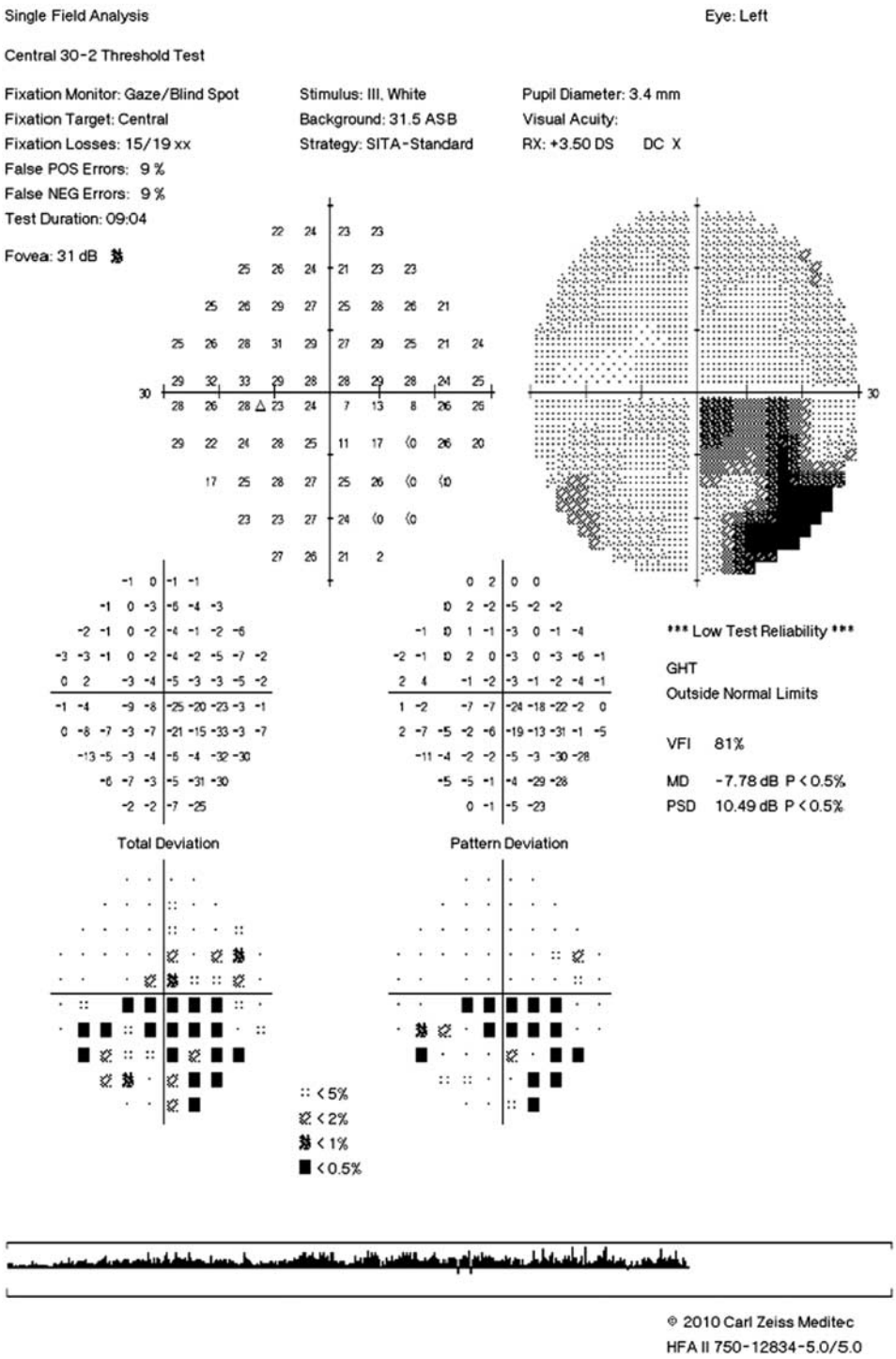

FIGURE 2. Left visual field results reveal decreased reliability of test taking and a pattern that suggests a right inferior quadrantanopia greater than a left inferior quadrantanopia.

stimulation unit (The Magstim Company Ltd, Dyfed, United Kingdom) with the handle held upward and the coil positioned tangentially to the scalp. The phosphene threshold was determined by finding the lowest stimulator amplitude capable of inducing a perception of light flashes, or phosphenes, on five of ten pulses when delivered over the visual V1 area. Thresholds of phosphene perception have been used to measure the excitability of the visual cortex (Afra et al, 1998; Boroojerdi et al, 2000; Kammer et al, 2001; Stewart et al, 2001). We used

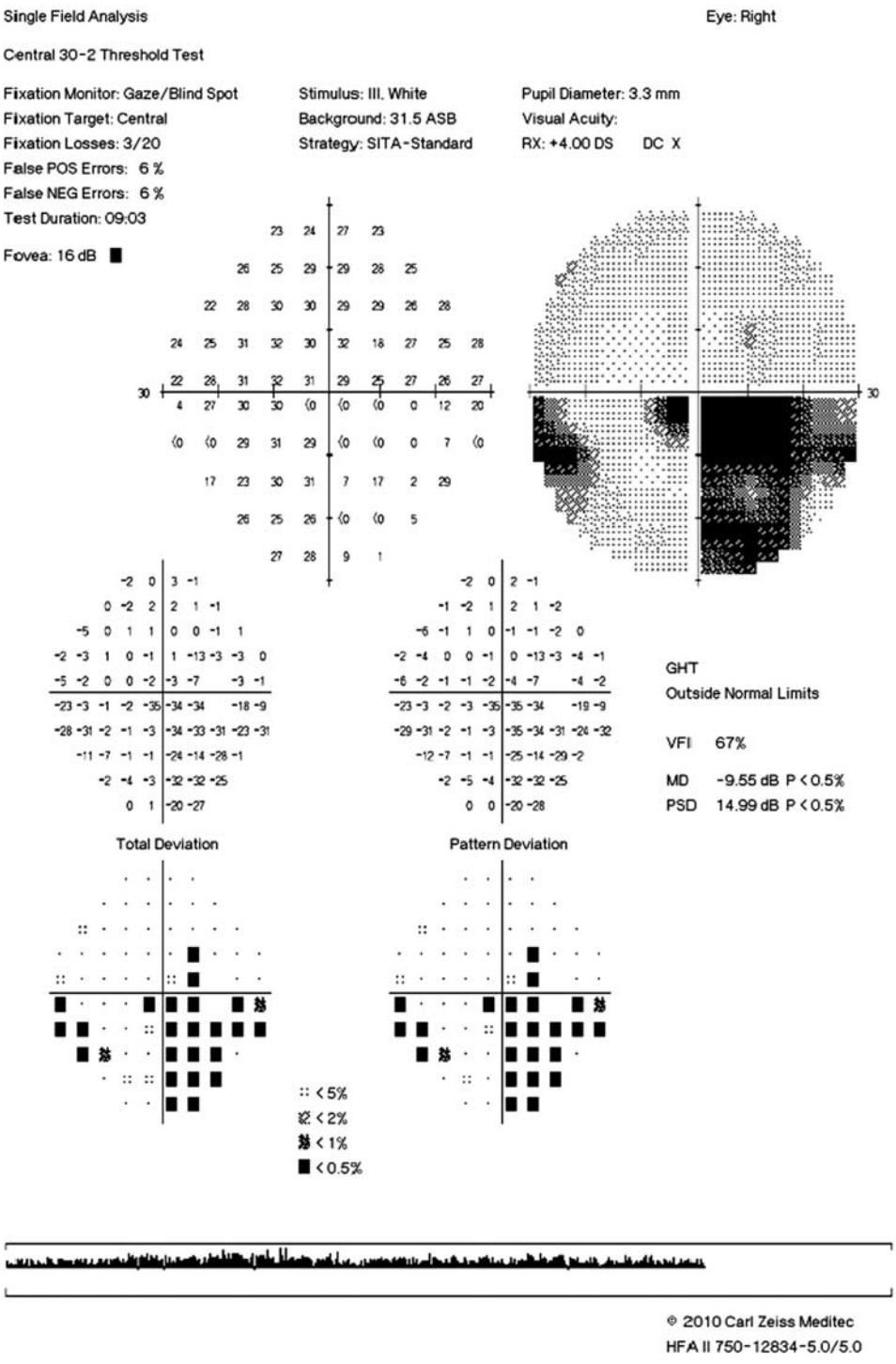

FIGURE 3. Right visual field results reveal decreased reliability of test taking and a pattern that suggests a right inferior quadrantanopia greater than a left inferior quadrantanopia.

low-frequency (1-Hz) rTMS, which has been demonstrated to induce a lasting (10-minute) decrease in visual cortical excitability in healthy subjects (Boroojerdi et al, 2000). In accordance with published research (Machii et al, 2006), all interventions were delivered at 90% phosphene threshold, except the last one, which was administered at 110%. Sessions were conducted 5 days per week for 2 weeks, and each lasted for approximately 30 minutes. A total of 900 stimulations were administered to each hemisphere in each session, for a total of 1800 stimulations per day.

TABLE 1. Treatment Parameters for Trials of Repetitive Transcranial Magnetic Stimulation

Trial Number	Cortical Target	Stimulation Parameters	Montreal Neurological Institute Coordinates	Interval Between Trials	Outcome
1	Left V5/MT	1-week duration 1 Hz, 90% phosphene threshold	Left V5: −48, −75, 8		No change
2	Bilateral V5/MT	2-week duration 1 Hz, 90% phosphene threshold	Left V5: −48, −75, 8 Right V5: 46, −78, 6	None	Improvement in large-amplitude oscillations
3	Bilateral V1	2-week duration 1 Hz, 90% phosphene threshold	Left V1: −16, −89, 3 Right V1: 16, −87, 3	10 weeks after trial 2	No change
4	Bilateral V5/MT	2-week duration 1 Hz, 110% phosphene threshold	Left V5: −48, −75, 8 Right V5: 46, −78, 6	10 months after trial 3	No change

Four different trials were conducted for a total duration of therapy of 7 weeks (Table 1). All parameters remained the same in each trial, aside from an increased intensity in the fourth trial. Cortical targets were defined using Montreal Neurological Institute (MNI) coordinates in Brainsight neuronavigation software (Rogue Research, Montreal, Canada) with the participant's magnetic resonance imaging. In the first trial, pulses were delivered to visual area left V5/MT (MNI coordinates: −48, −75, 8) for a 1-week period because V5/MT is thought to be causally linked to the perception of illusory motion and because we hypothesized that V5/MT had become hyperexcitable as a result of cortical injury (Ruzzoli et al, 2011). Owing to a lack of complete resolution of the patient's symptoms after the V5/MT trial, a second trial was performed with pulses delivered bilaterally to area V5/MT over a 2-week period because we suspected that the patient's TBI might have induced pathologic remodeling leading to hyperexcitability of the contralateral V5/MT (MNI coordinates: −48, −75, 8 and 46, −78, 6). In a third trial 10 weeks later, pulses were delivered bilaterally to visual area V1 (MNI coordinates: −16, −89, 3 and 16, −87, 3) for 2 weeks because of the location of the occipital lesion and the importance of V1 in visual awareness of motion (Pascual-Leone and Walsh, 2001). In the fourth and final trial, 10 months later, pulses were delivered bilaterally to visual area V5/MT (MNI coordinates: −48, −75, 8 and 46, −78, 6), again for 2 weeks but with higher intensity (110% versus 90% phosphene threshold).

Outcome Measures

Because the patient described oscillations with head movements and functional movements as well as static positions, we assessed whether he was having difficulty with gaze stabilization and vestibular processing, which are known to be affected by trauma, before rTMS therapy (Jury and Flynn, 2001). Dynamic visual acuity testing (DVAT) and gaze stabilization testing (GST) were used to assess visual stability pre- and post-intervention (Voelker et al, 2015). DVAT and GST were performed using the Neurocom SMART Balance Master Invision software, version 9.0 (Natus Medical Inc., Pleasanton, California).

DVAT has been used to quantify oscillopsia due to decreased gaze stability and vestibular ocular reflex (VOR) function (Demer et al, 1994). The validity and reliability of DVAT for assessing central oscillopsia are unknown, but we used it given the absence of other defined outcome measures for central oscillopsia. GST was used as a secondary measure, as it minimizes contributions from vestibular catch-up (saccades or preprogrammed saccades). As an additional secondary outcome measure, we interviewed the patient after completion of each rTMS treatment session to elicit subjective improvements in visual symptoms and/or function.

While DVAT and GST are not physiological tests of the VOR, they test the functional capacity of the VOR, which involves other systems as well. Thus, abnormal results from DVAT and GST are not specific to VOR dysfunction but indicate that the functional capacity of the VOR is in some way impaired, which aligns with symptoms reported by the patient.

Static Visual Acuity

Static visual acuity was assessed using a single optotype, the letter "E" flashing in the center of a computer monitor. Testing starts at 0.3 logMAR and flashes for 1 second on the screen. The computer program changes the orientation and size with each trial, and the participant answers with the orientation of the optotype until a threshold acuity is determined. This threshold acuity is then used to determine target size for DVAT and GST.

Minimum Perception Time

Minimum perception time is defined as the shortest amount of time an optotype can be presented on a screen for which the participant can accurately identify its orientation. Minimum perception time is measured in milliseconds (msec). The optotype appears in the center of a screen 0.25 logMAR above the participant's static visual acuity. It appears for 250 msec, after which it disappears and the participant identifies the orientation of the "E" optotype. The computer program then presents optotypes with different orientations at increasingly shorter presentation times until a minimum threshold is determined. The minimum perception time sets the display time parameters for DVAT and GST.

A head-mounted sensor was used to determine actual head velocity during testing and correlate it with computer-prescribed head velocity for target presentation. Participants were instructed to maintain smooth headshakes as if they

were shaking their head "no" while maintaining their gaze on a blank circle on the center of the screen, where the optotype would then appear. A visual scale at the bottom of the screen demonstrated the participant's actual head velocity as well as the targeted speed prescribed by the computer program.

Dynamic Visual Acuity Testing

During DVAT the participant moves his or her head at a minimum velocity of 85 degrees per second, and the size of the optotype varies according to the participant's performance. DVAT measures the minimum optotype size at which the orientation was correctly identified while moving the head. Once the minimum velocity is achieved, the optotype appears on the screen in one of four directions that the participant then identifies. DVAT data are separated in leftward and rightward head movements using unpredictable target presentation timing and head direction. DVAT was used as the primary outcome measure for this study. Data are presented as a loss in visual acuity on the logMAR scale as compared to the static visual acuity assessment.

Gaze Stabilization Testing

GST measures the maximum head velocity at which a participant is able to maintain visual acuity. This maximum head velocity was determined by a computer-generated algorithm. When the participant's head movement met the target head velocity for the trial, the optotype "E" would appear at an acuity of 0.25 logMAR above the participant's static visual acuity in one of four directions. GST data are presented as maximum velocity for rightward and leftward head movement.

RESULTS

Table 2 summarizes the patient's minimum perception time, DVAT, and GST results after each rTMS trial. The patient demonstrated higher values in minimum perception time for the perception time test during trials 3 and 4 compared to mean and standard deviation values for age-matched healthy subjects (28 ± 10.14 msec) (Honaker and Shepard, 2010; Li et al, 2014). Increased perception time allows for the use of other visual systems in the identification of optotype presentation, which can render the DVAT and GST results less reliable (Riska and Hall, 2016). During all but one assessment the patient demonstrated mean perception times within acceptable ranges (20 to 70 msec). During the final assessment the patient demonstrated an abnormal mean perception time (100 msec), which may have made VOR identification during DVAT and GST less reliable. The increased perception time may be due to inattention to the task during various perception time trials or may be a result of an unstable visual field during static position testing. Data from DVAT were within one standard deviation for healthy age-matched subjects (0.180 ± 0.225 logMAR), indicating that dynamic visual acuity was not impaired (Li et al, 2014). No change in DVAT results was observed for any trial. Normative data for adults aged 50 to 59 have been established for GST. Mean and standard deviation scores for GST in healthy adults are 147.40 ± 28.54 degrees per second (Honaker and Shepard, 2010; Li et al, 2014). The patient demonstrated GST results lower than for age-matched healthy subjects (Table 2). This indicates that the patient was not able to show faster head speeds while maintaining a stable visual field. The patient did not demonstrate improvement in GST following rTMS treatment (Table 2).

The patient reported symptomatic improvement in oscillopsia 1 to 2 weeks after the second trial of rTMS, in which visual area V5/MT was targeted bilaterally. He noted that the large-amplitude oscillations that he had experienced resolved following therapy, and remained resolved at a clinic visit 12 months after rTMS, but that he continued to experience small-amplitude oscillations. The patient also reported a slight improvement in balance following rTMS therapy. He denied any benefit from subsequent rTMS trials in terms of oscillopsia, visual acuity, visual function (eg, reading), or other functional abilities. The patient reported no side effects from treatment, and there were no adverse events.

LITERATURE REVIEW

Central oscillopsia has rarely been reported in the literature (Table 3) (see Tilikete and Vighetto, 2011, for a

TABLE 2. Baseline and Post-Treatment Results for DVA Loss and GST

	Best Minimum Perception Time (msec)	DVA Loss			Snellen Fraction		LogMAR		GST (degrees/second)	
		Left (logMAR)	Right (logMAR)	Symmetry	Left	Right	Left	Right	Left	Right
Baseline	30	0.33	0.04	18% Right	20/135	20/69	0.83	0.54	111	119
Trial 1	20	0.4	NS	NS	20/126	NS	0.8	NS	99	NS
Trial 2	20	0.29	0.19	7% Right	20/107	20/85	0.73	0.63	92	98
Trial 3	70	0.16	0.31	10% Left	20/80	20/112	0.6	0.75	92	98
Trial 4	100	−0.2	0.17	18% Left	20/28	20/66	0.15	0.52	90	98

DVA = dynamic visual acuity. **GST** = gaze stabilization testing. **logMAR** = base-10 logarithm of the minimum angle of resolution measured in arcmin (1 arcmin = 1/60 degree). **NS** = not scored due to inability to get a reliable response.

TABLE 3. Reported Cases of Central Oscillopsia

Reference	Case	Etiology	Lesion Location	Characteristics of Oscillopsia	Associated Symptoms	Treatment(s) and Outcome
Present article	57-year-old white man	Traumatic brain injury	Bilateral parietal and occipital lobes, and V5/MT	Horizontal oscillations exacerbated by central fixation, not suppressed by eye closure, and worsening throughout the day	Decreased visual acuity and impaired balance	Refractory to amantadine hydrochloride, carbamazepine, and methylphenidate; transcranial magnetic stimulation improved large oscillations, but small oscillations persisted
Jacome (2013)	18-year-old woman	Migraine without infarction	None noted	Rapid development of peripheral oscillations initiated by central fixation without specific direction	Lightheadedness, photophobia, mild postural imbalance, mid-facial pain	Resolution after several weeks of incremental doses of oral topiramate
Kim et al (2012)	45-year-old woman	Neuromyelitis optica spectrum disorder	Corpus callosum, bilateral occipital lobes, and V5/MT	Evoked during spontaneous gaze and head movement; oscillations in opposite direction of movement	Lower-extremity weakness and dizziness after resolution of oscillopsia	Refractory to intravenous steroids for 5 days; resolution after 2 months of plasmapheresis
Nunez et al (2014)	46-year-old Vietnamese man	Stroke/middle cerebral artery dissection	Distal M1 segment of left middle cerebral artery	Front and back oscillations	Sudden-onset headache, confusion, disorientation, difficulty concentrating, unsteady gait	Resolution after 2 weeks of daily aspirin, smoking cessation, glycemic control, cholesterol control
Suzuki et al (2004)	31-year-old man	Unknown	None noted	Vertical and horizontal oscillations with varying amplitude	None noted	Refractory to 1 year of daily trazodone

review). Kim et al (2012) reported a case in a 45-year-old woman caused by neuromyelitis optica spectrum disorder. This patient had antibodies targeting aquaporin 4 and displayed lesions in the corpus callosum, occipital lobe, and V5/MT bilaterally. The oscillopsia was refractory to intravenous steroids administered at 1 g/day for 5 days but improved over the span of 2 months following treatment with plasmapheresis. Cortical lesions in V5/MT and the primary visual cortex were improved on repeat imaging following plasmapheresis (Kim et al, 2012).

Nunez et al (2014) reported a case of central oscillopsia in a 46-year-old Vietnamese man with ischemic lesions in the territory of the distal M1 segment of the left middle cerebral artery due to high-grade stenosis and an intimal flap consistent with dissection. The patient presented with a 2-week history of intermittent headache associated with blurred vision. The initial episode began as a sudden-onset headache located in the frontal lobe with visual dysfunction he described as objects moving back and forth repeatedly. These symptoms resolved spontaneously over the following 3 days. A second episode occurred 4 days prior to admission, during which he experienced a recurrent headache and the perception of bouncing objects. He experienced confusion, disorientation, and difficulty concentrating in the period between the two episodes. He denied any trauma, family history of cardiovascular illness, or other symptoms. Symptoms from the second episode did not resolve while he was hospitalized, and he was treated with daily aspirin, smoking cessation, and glycemic and cholesterol control. His symptoms resolved by the time of discharge (Nunez et al, 2014).

Jacome (2013) reported oscillopsia in an 18-year-old woman with rapid development of peripheral oscillations without specific direction initiated by central fixation on a given target and associated with lightheadedness, photophobia, mild postural imbalance, and mid-facial pain. Her neurologic and ophthalmic examinations, electroencephalography, and magnetic resonance imaging were normal. An atypical variant of migraine, persistent visual aura without infarction, was proposed as the cause of her central oscillopsia. Her symptoms dissipated after several weeks of treatment with incremental doses of oral topiramate.

Suzuki et al (2004) described a case of central oscillopsia in a 31-year-old man with no history of serious illness, trauma, or cortical lesions. The patient reported that objects oscillated vertically and horizontally with varying amplitude and denied any change in oscillations with distance. Compared to healthy individuals, the V5/MT area of the patient's visual cortex demonstrated increased regional cerebral blood flow on positron emission tomography while observing stationary stimuli,

suggesting overactivity of the visual motion center. He was prescribed 100 mg/day of trazodone for a year, with no improvement in symptoms.

Oscillopsia without nystagmus and vestibulo-ocular dysfunction has been identified in patients suffering from psychological trauma. In one study, Tym et al (2009) reported clinical observations of 100 patients presenting with visual disturbances following an acute-fear experience. Fifty-four patients were found to have both abnormal hallucinatory flashbacks of the most fear-inducing moment and what has been termed "persistent peripheral oscillopsia" (PPO). PPO is characterized by horizontal oscillations of objects in the periphery evoked immediately or within 10 seconds of focusing on a stationary object. In the most severe cases, the condition spreads to include the center of the visual field. PPO is so-named because of initial movement in the peripheral field; it is not associated with abnormal eye movements or other ocular pathology and thus is presumed to arise from a central etiology. Tym and colleagues treated patients by evoking the abnormal hallucinatory flashback and then inducing rapid eye movements using a revised protocol of an eye movement desensitization and reprocessing procedure (Shapiro, 1989). Of the 54 patients treated, 40 eventually had complete elimination of both the abnormal hallucinatory flashback and PPO, which were observed to degrade in a stepwise manner following each treatment session (Tym et al, 2009).

DISCUSSION

Our patient reported two types of visual oscillopsia that can be distinguished in terms of phenomenology, large versus small amplitude, as well as response to physiological manipulation (rTMS). Our review of the literature similarly describes distinct large- and small-amplitude oscillations, and we hypothesize that the larger-amplitude oscillations were caused by V5/MT damage while the smaller-amplitude oscillations may reflect less focal results of trauma. The literature on PPO suggests that these smaller-amplitude oscillations may in fact be more psychological in nature, and our patient did report some symptoms of post-traumatic stress disorder, which were more severe in the years immediately after his trauma.

We suspect that the mechanism of our patient's symptoms was disrupted visual input to V5/MT that induced a state of hyperexcitability in V5/MT. Damage associated with TBI has been shown to induce pathologic remodeling, which may prompt a state of hyperexcitability in cortical regions (Park et al, 2008). Moreover, preserved perception of movement, which would be expected to be impaired with direct damage to V5/MT, suggests damage to inputs and alteration of V5/MT function rather than direct or total damage. Results after rTMS therapy indicate that this mechanism may be the etiology of at least a portion of his oscillopsia. The patient's reported persistent symptomatic improvement following the second trial of V5/MT rTMS administration suggests that rTMS successfully downregulated cortical hyperexcitability caused by trauma-induced pathologic remodeling in V5/MT. Although our patient's symptoms were stable for years before treatment and it is unlikely that symptoms spontaneously remitted, lack of a control condition means that a placebo effect is possible, and further studies are needed to confirm the responsiveness of large-amplitude central oscillopsia to rTMS.

The fact that DVAT and GST were unchanged after rTMS therapy suggests that cortical hyperexcitability, rather than vestibular dysfunction, underlies his oscillopsia. It is also possible that DVAT and GST may have failed to detect objective treatment effects. Because DVAT does not correlate with the degree of peripheral oscillopsia, it is possible that there was an improvement in oscillopsia but it was beneath the threshold for DVAT of our participant (Guinand et al, 2012). DVAT is often used to evaluate vision degradation in people with nystagmus, but it may not be the most appropriate measure in people with central oscillopsia.

It is also possible that cortical remodeling following the TBI may have led to central oscillopsia through a mechanism similar to that which drives detection of illusory motion in healthy individuals. In healthy individuals, viewing a particular image evokes illusory motion, known as the Enigma illusion. Viewing this image drives microsaccades that then create the perception of motion (Troncoso et al, 2008). In our patient, cortical remodeling may have resulted in a central stimulus that evokes microsaccades even when viewing stationary objects, causing these objects to appear to oscillate. These microsaccades would not have been able to be measured by any of the testing performed on the patient.

Lack of response to subsequent rounds of bilateral V5/MT rTMS administration may be due to the increased severity of lesions in the left hemisphere that were presumably attenuated during the second trial. Although we hypothesized that increased-intensity stimulation in V5/MT might resolve small-amplitude oscillations by further downregulating hyperexcitability, it is possible that the patient had already achieved maximal symptom improvement attainable by rTMS. It is also possible that changing parameters other than intensity, specifically basing our parameters on a V5 rather than phosphene threshold, or combining rTMS with a visual or behavioral task, could result in greater clinical benefits (Romei et al, 2016; Silvanto et al, 2005).

The lack of objective improvement in oscillopsia after V1 stimulation suggests that this region was not directly involved in producing the patient's oscillopsia, a finding that is corroborated by previous research on illusory motion pathways. While V1 provides input to V5/MT, retinotectal-pulvinar pathways bypass V1 and directly input to V5/MT. Perception of illusory motion in healthy individuals has been shown to upregulate activity in V5/MT but not V1, suggesting that illusory perception of motion may be driven by V5/MT alone (Kuriki et al, 2008). In one study, illusory motion detection evoked when viewing the Enigma illusion in healthy individuals

was inhibited when V5/MT was downregulated by rTMS, but not when V1 was downregulated by rTMS, further supporting the idea that V5/MT is the source of illusory motion (Ruzzoli et al, 2011). The patient's paradoxical increase in oscillations with fixation may be due to utilization of attentional resources, which has been shown to upregulate activity in V5/MT, adding to his presumed cortical hyperactivity (Huk et al, 2001).

It is possible that central vestibular deficits resulting from the TBI contributed to our patient's oscillopsia. Low-normal gaze stability and VOR testing, as well as normal videonystagmography and vestibular evoked myogenic potentials results, suggest that the patient did not have vestibular dysfunction. Moreover, to our knowledge, there is no evidence that DVAT and GST can be abnormal in cases of cortical dysfunction outside of vestibular pathways. However, it is possible that vestibular testing sensitivity was inadequate for detecting vestibular dysfunction. Moreover, DVAT and GST results were low-normal, suggesting a possible component of vestibular dysfunction, especially given the patient's complaints of imbalance. Vestibular dysfunction may also explain why rTMS did not fully eliminate his symptoms.

In conclusion, modulation of cortical hyperexcitability with rTMS combined with the patient's symptomatic improvement following V5/MT rTMS stimulation suggests that trauma-induced cortical hyperexcitability caused a portion of the central oscillopsia in this case. Further research into the pathophysiological mechanisms of central oscillopsia, specifically those caused by hyperexcitability syndromes, is needed to direct treatment strategies in this patient population. Future studies should also carefully describe phenomenology, as large- and small-amplitude oscillations may reflect different mechanisms and thus merit different treatments.

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