J Biol Phys (2008) 34:381–392
DOI 10.1007/s10867-008-9092-1

ORIGINAL PAPER

Eye–Target Synchronization in Mild Traumatic Brain-injured Patients

R. Contreras · R. Kolster · H. U. Voss · J. Ghajar · M. Suh · S. Bahar

Received: 30 January 2008 / Accepted: 6 June 2008 /
Published online: 24 July 2008
© Springer Science + Business Media B.V. 2008

Abstract Eye–target synchronization is critical for effective smooth pursuit of a moving visual target. We apply the nonlinear dynamical technique of stochastic-phase synchronization to human visual pursuit of a moving target, in both normal and mild traumatic brain-injured (mTBI) patients. We observe significant fatigue effects in all subject populations, in which subjects synchronize better with the target during the first half of the trial than in the second half. The fatigue effect differed, however, between the normal and the mTBI populations and between old and young subpopulations of each group. In some cases, the younger ($\leq$40 years old) normal subjects performed better than mTBI subjects and also better than older ($>$40 years old) normal subjects. Our results, however, suggest that further studies will be necessary before a standard of "normal" smooth pursuit synchronization can be developed.

R. Contreras (✉) · S. Bahar
Department of Physics and Astronomy, Center for Neurodynamics,
University of Missouri, St. Louis, MO, USA
e-mail: rpcontre@gmail.com, rc5df@umsl.edu

S. Bahar
e-mail: bahars@umsl.edu

R. Kolster
Department of Psychiatry, Sackler Institute, New York, NY, USA

H. U. Voss
Department of Radiology and Citigroup Biomedical Imaging Center, Weill Cornell Medical College,
New York, NY, USA

J. Ghajar
Brain Trauma Foundation, New York, NY, USA

J. Ghajar · M. Suh
Department of Neurological Surgery, Weill Cornell Medical College, New York, NY, USA

M. Suh
Department of Biological Science, Sungkyunkwan University, Seoul, South Korea

Keywords Mild traumatic brain injury (mTBI) · Smooth pursuit eye movement · Phase synchronization

1 Introduction

Mild traumatic brain injury (mTBI) is commonly associated with attentional deficit [1, 2] and performance variability [3–7] as well as with diffuse axonal injury [8, 9]. Rostro-frontal white matter tracts are particularly affected [10, 11], which may lead to deficits in the interaction between cerebellar and frontal regions in the control of motor behaviors, such as smooth pursuit eye movement (SPEM) [6, 7], which has been shown to depend on attention [12–15].

As with other injuries, early identification and treatment is critical for good patient outcome, and thus early and accurate identification of traumatic brain injury, as well as assessment of its severity, are paramount in the treatment of mTBI patients. Most methods of mTBI assessment require long and expensive testing sessions, making the assessment of brain injury difficult and inefficient for researchers, clinicians, and patients alike. Furthermore, most of these measures lack specificity, making it difficult to disentangle the different effects of brain injury on various cognitive functions. In particular, there currently exist few methods for the accurate measurement of deficits in sustained attention [2]. In populations characterized by high levels of intraindividual variability, measures of mean performance may lead to inaccurate inferences [16]. Therefore, the development of rapid yet sensitive and reliable measures to continuously assess dynamically changing attentional states is of critical importance in order to detect subtle cognitive impairments due to mTBI and to generate accurate diagnoses for mTBI patients.

Previous studies have found that variability in SPEM is correlated with cognitive performance [6, 7] and can be predictive of the degree of white matter shear injury in mTBI patients as assessed with diffusion tensor imaging (Suh et al., submitted). In this paper, we apply a rigorous mathematical measure, stochastic phase synchronization, to the analysis of SPEM in mTBI and normal subjects. This measure, developed by the nonlinear dynamics community, has recently been successfully applied to the study of other neurological pathologies such as epilepsy [17, 18] and Parkinson's disease [19].

SPEM enables subjects to track slowly moving objects in the visual field. Previous work [12–15] suggests that SPEM depends on attentional processes. Indeed, the neural structures implicated in attention (the frontal eye fields, supplementary eye fields, prefrontal cortex, and parietal cortex) are directly connected with regions such as the cerebellum, involved in SPEM. The connecting tracts between these regions often suffer significant shear damage during mTBI [10, 11]. Since fatigue can affect eye movement [20–23] and since various factors such as aging [24], fatigue [25], and boredom [26] can affect attention, we investigate the effects of these parameters on SPEM.

2 Materials and Methods

2.1 Smooth Pursuit Eye Movement

A total of 23 normal control and 22 mTBI subjects were studied. Normal control subjects had no history of head injury or trauma. The mTBI subjects were between ages of 20 and 53 years, and all had a Glasgow Coma Scale score of 15 at the time of injury, except one, who had a score of 14. Conditions for inclusion for mTBI patients were blunt,

isolated mTBI, presence of post-traumatic amnesia, no cranial nerve abnormalities (except those affecting the sense of smell), and nonintoxication. Patients were excluded on the basis of prior mTBI with loss of consciousness greater than 24 h, history of multiple mTBI with loss of consciousness, pregnancy, history of drug or alcohol abuse, preinjury neurological or psychiatric diagnosis of an axis I or axis II disorder, general anesthesia within 2 weeks before testing, seizure following trauma, seizure disorders, and preinjury use of psychotropic medication(s). All subjects gave written consent approved by the Weill Medical College of Cornell University Institutional Review Board.

Eye movements were recorded by a human infrared eye tracking system (Eyelink II) with 500 Hz temporal resolution at the Citigroup Biomedical Imaging Center. The target visual stimulus, created using a Python program, was presented on a computer screen 40 cm from the subject. Before testing, an eye chart was used to verify that all subjects had normal or corrected-to-normal vision. Subjects were seated in a darkened room, and their heads were stabilized via a bite bar system. Calibration based on nine points, including center and peripheral, was performed before each session, which ensured that all subjects had a full range of oculomotor movement. If subjects expressed signs of fatigue or discomfort, they were encouraged to pause testing, after which the session was resumed. During the SPEM task, the subjects tracked a target stimulus, a red circle of 0.2° diameter, which followed a circular trajectory of 7° radius at a rate of 0.4 Hz, in the clockwise direction. Each trial had a duration of 30 s. Figure 1 shows the performance of a normal subject (a) contrasted with that of an mTBI patient (b), for one full cycle of target movement.

2.2 Synchronization Analysis

The circular target path used in this SPEM paradigm allows us to define phase angle in our synchronization analysis directly as the angle of the time point on the circle. The phase angle φ is defined as

$$\varphi = \arctan\ (y/x) \tag{1}$$

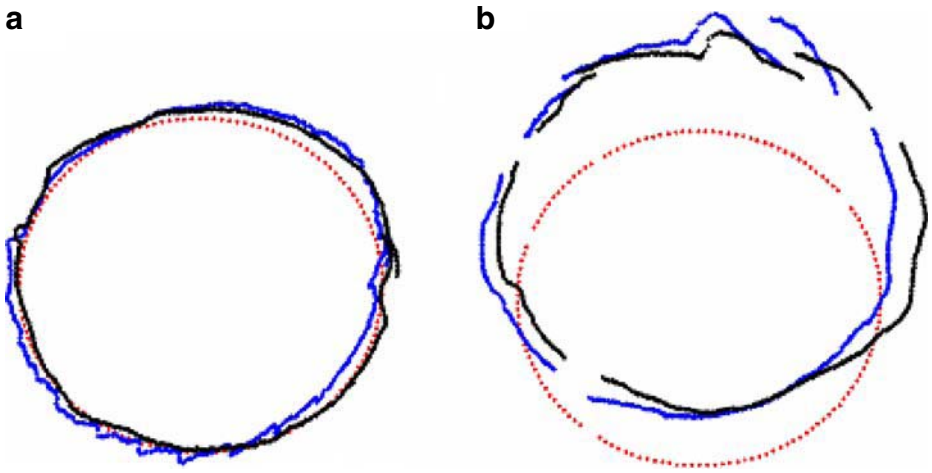

Fig. 1 Target path (*red dots*) and eye position (*blue*, left eye; *black*, right eye) for a normal subject (**a**) and a TBI patient (**b**) during one full cycle of target tracking. Gaps in the eye position path are due to blinking

where (x, y) is the position of the eye or the target, as a function of time, relative to the center of the circle. In this analysis, the center of the target's circle is used as the "center" for analysis of both the motion of the target and the path followed by the eye. See Section 4 below for a discussion of the motivation for this choice, possible alternative definitions of the center of the circle, and the implications of these choices.

With the phase angle defined as in (1) above, the phase difference between eye and target is

$$\Phi(t) = \varphi_{\mathrm{t}}(t) - \varphi_{\mathrm{e}}(t) \tag{2}$$

where $\varphi_t(t)$ is the phase angle of the target and $\varphi_e(t)$ that of the eye.

We define synchronization following the stochastic phase synchronization approach [27–30]. In this approach, synchronization is quantified by extracting the probability density of the phase differences. The intensity of the first Fourier mode of this density is given by

$$\gamma^2 = <\cos(\Phi(t))>^2 + <\sin(\Phi(t))>^2 \tag{3}$$

where $<\cos(\Phi(t))>$ and $<\sin(\Phi(t))>$ are time averages. From (3), the synchronization index γ is defined such that $0 \leq \gamma \leq 1$, where $\gamma = 0$ indicates complete lack of synchronization, while $\gamma = 1$ indicates a completely synchronized state.

Figure 2 illustrates the application of phase synchronization to SPEM data from both a normal (top) and mTBI (bottom) subject. The left-hand panels show the phase difference (2) as a function of time. The right hand panels show the phase differences collapsed into histograms; the synchronization index defined in (3) measures the sharpness of these distributions. Note the much greater variation in performance of the mTBI subject and the much broader histogram peak, indicating less eye–target synchronization in the case of this individual than for the normal subject. Note also that, for both the normal and mTBI subject, there is more variation in phase as a function of time during the second half of the trial, indicating a fatigue effect; this is discussed in more detail in Section 3.2 below.

3 Results

3.1 Synchronization and Saccade Removal

Saccades are abrupt, rapid eye movements, which, for the particular task of following a target on a circular path, often affect the orbit's amplitude (in this case, the radius of the circular orbit) rather than its phase. For the analysis of SPEM, saccades are typically removed from the data, based on velocity threshold criteria, followed by linear interpolation in order to bridge the "gaps" left by the removal of data points [6, 7]. However, phase synchronization provides a distinct advantage for the analysis of SPEM in that it obviates the need for saccade removal. The phase synchronization index is relatively insensitive to saccades, precisely because it deals with phase rather than amplitude. The variable of interest for stochastic phase synchronization is concerned with movement along the orbit, whereas saccades generally occur out of the orbit, and often normal to the orbit's path. Note, however, that there may be a component of saccadic eye movement that lies within the path; this may correspond to so-called "catch-up" saccades, in which the eye attempts to catch up with the target after lagging behind. The in-orbit components of such a saccade will be retained by the use of phase as a measure, while the normal-to-orbit component will not.

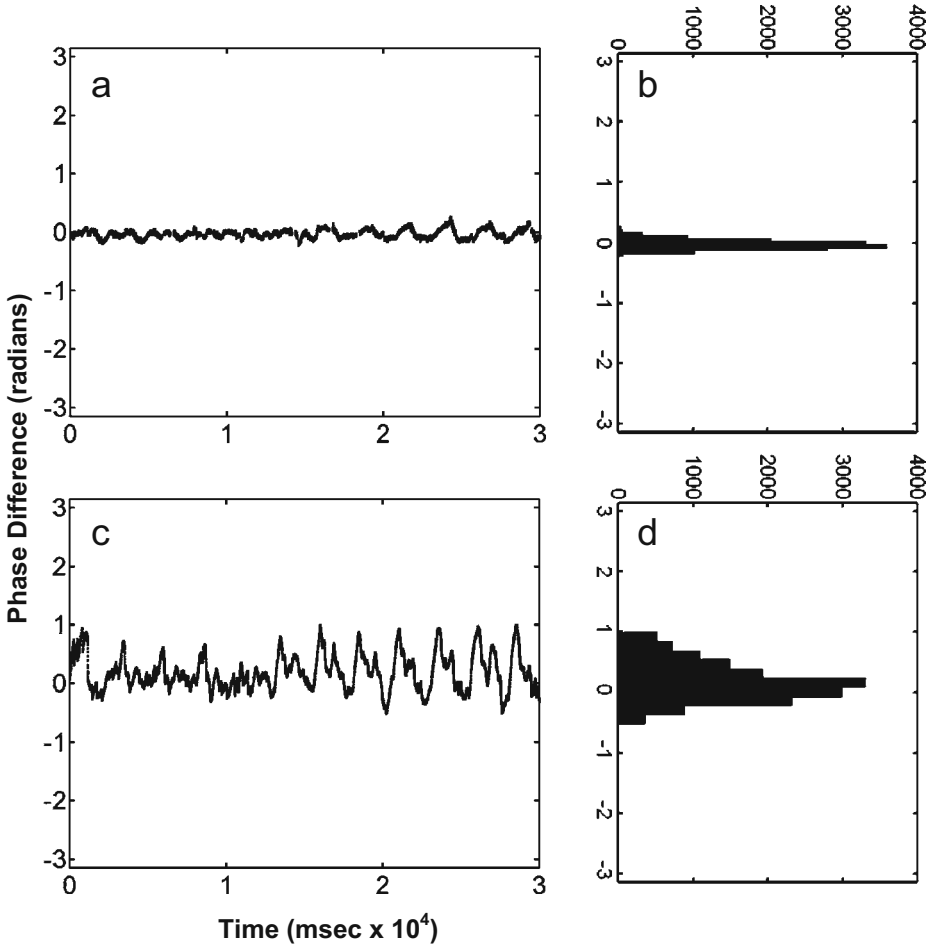

Fig. 2 Phase differences between eye and target for normal (**a**) and TBI (**c**) subjects. The corresponding phase difference histograms are shown in **b** and **d**

The efficacy of phase synchronization in this regard is clearly illustrated in Fig. 3. Figure 3a illustrates the angular velocity difference between the eye and the target. Sharp jumps in this difference, when the eye speeds up briefly and rapidly during a saccade, appear as the sharp peaks. However, a plot of the phase difference between eye and target, as shown in Fig. 3b, causes the saccade peaks to practically disappear.

It is important to emphasize that the phase synchronization approach is deliberately selected for the present analysis in order to separate the analysis of phase difference from the analysis of position error. Other analysis methods exist which are better suited for determining errors in amplitude during SPEM [6, 7].

3.2 Fatigue Effects

Figure 2 illustrates the eye–target phase difference as a function of time for a normal (top) and mTBI (bottom) subject. While there is an evident difference between the eye–target

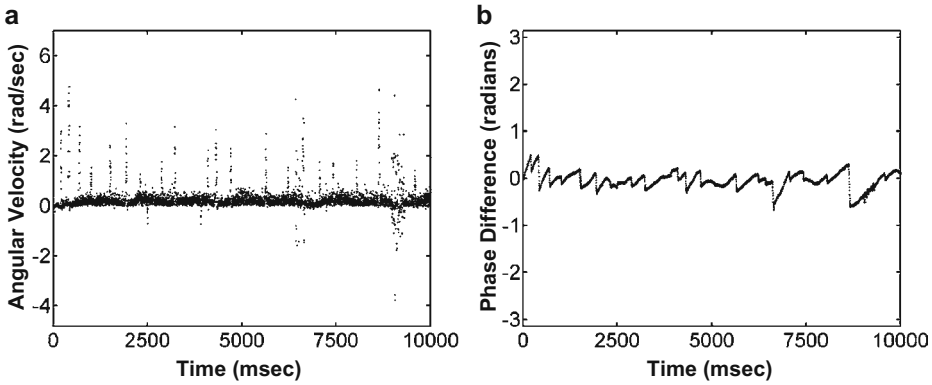

Fig. 3 Angular velocity (**a**) and phase difference (**b**) as a function of time for the same subject

synchronization for the two subjects, both subjects also exhibit a fatigue effect. In both cases, the phase difference is tighter and more controlled during the first half of the trial, indicating that the subjects are performing their smooth pursuit task more efficiently early in the trial. In order to quantify this fatigue effect, we calculated the synchronization index separately for the first half and the second half of each trial, for each subject, as shown in Table 1. Normal and mTBI subjects were also divided into age groups ($\leq$40 and $>$40), as will be discussed in more detail in Section 3.3 (note that N in Table 1 refers to the number of eyes studied; data was collected from both eyes for each subject. There is variability between the left and right eye within a single subject, and thus data from each eye was treated as a separate "experiment").

For all groups, we find a statistically significant drop in the synchronization index between the first half of the trial and the second, indicating that both normal and mTBI subjects perform less well in the SPEM task as they grow fatigued (or possibly bored; see Section 4). Using a paired t test, we find significant drops for all four subject groups (young normals, $p = 0.0227$; older normals, $p = 0.0055$; younger mTBI subjects, $p = 0.0006$; older mTBI subjects, $p = 0.0137$). The effect of fatigue in the different populations is also illustrated by the distributions of synchronization indices, shown as histograms in Figs. 4 (normal subjects) and 5 (mTBI subjects). Note how the distributions become markedly broadened during the second half of the trials (right hand column in both figures).

Table 1 Synchronization index

	Young normal		Old normal		Young mTBI		Old mTBI	
	First half (N= 24)	Second half (N= 24)	First half (N= 20)	Second half (N= 20)	First half (N= 24)	Second half (N= 24)	First half (N= 20)	Second half (N= 20)
Mean	0.9264	0.8690	0.8691	0.7707	0.9282	0.8584	0.9380	0.8202
Standard deviation	0.1054	0.1961	0.1065	0.1991	0.1323	0.1990	0.0634	0.2044

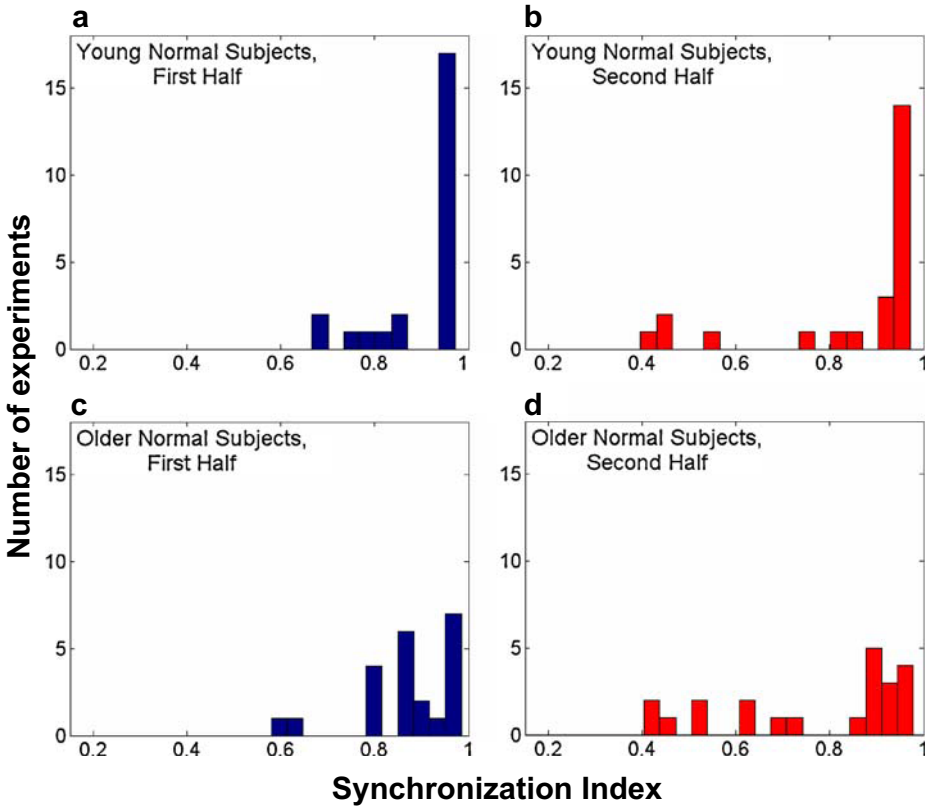

Fig. 4 Distributions of synchronization indices for normal subjects, divided into age groups and with the first and second halves of each trial separated. The *top row* (**a** and **b**) shows younger subjects (<40 years old); the *bottom row* (**c** and **d**) shows older subjects (>40 years old). The *left-hand panels* (**a** and **c**) show synchronization in the first half of each trial, while the *right-hand panels* (**b** and **d**) show synchronization in the second half

3.3 Age Dependence of Fatigue Effects

As mentioned above, the subjects were separated into two populations, "young" (≤40 years old), and "old" (>40 years). While fatigue effects were observed for all groups, as discussed in Section 3.2, some differences in these effects were observed between groups. In particular, the fatigue effect in the young normal population depends sensitively on the inclusion of two young subjects who, by some criteria, could be excluded as outliers. These two subjects exhibited a fatigue effect, defined as the absolute drop in synchronization index, more than two standard deviations outside the mean within the entire population of young normal subjects. Note that no other subjects, in any group, exhibited a drop this far away from the mean of their group. The most stringent criteria for exclusion of outliers, however, requires that outliers can only be excluded if they lie more than two standard deviations from the mean of the entire data set, including *all* groups. Since these two normal subjects did not meet this most stringent criterion, they have been included in the statistical analysis presented above and in Table 1. However, since their performance

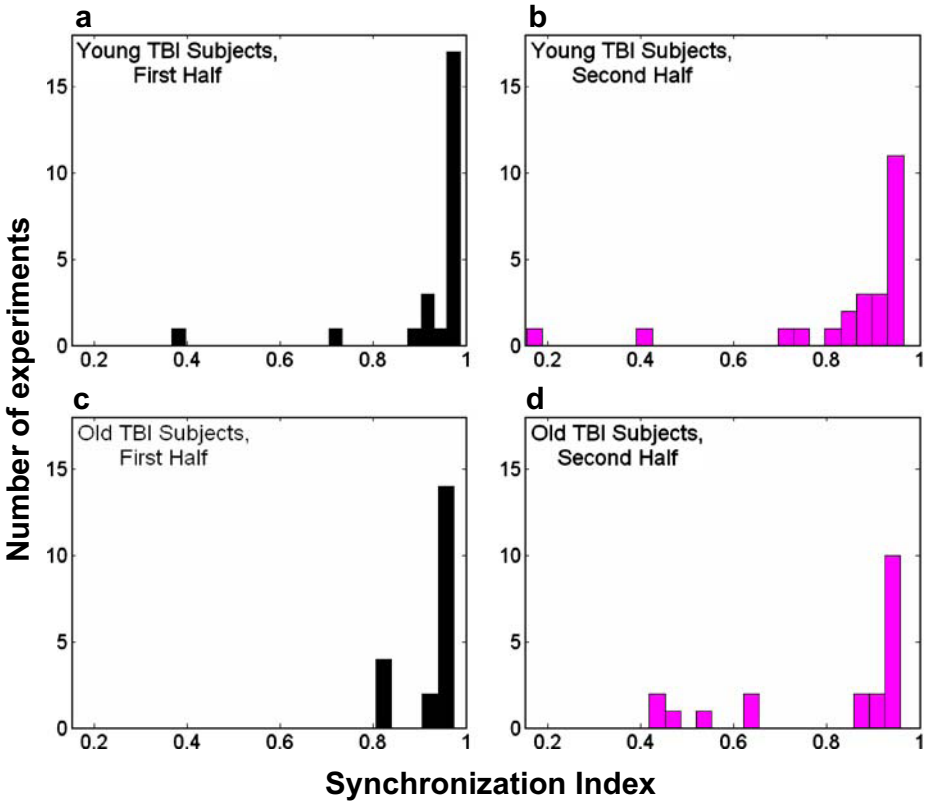

Fig. 5 Distributions of synchronization indices for TBI patients. Contrary to normal subjects (see Fig. 4), younger and older TBI patients do not show a marked difference

differs so significantly from that of others in their cohort, we discuss below what would result had they been excluded from the analysis.

Without these two subjects, the drop in synchronization for the young group of normal subjects would no longer be significant (paired t test, $p = 0.2180$). Moreover, within the normal population, the fatigue effect, measured as absolute drop in synchronization between the first and second halves of each trial, would be significantly greater in the older population (unpaired t test with Welch correction, $p = 0.0119$) if these subjects were excluded. There would also be a significantly greater fatigue effect in the young mTBI population compared to the young normal group ($p = 0.0033$) and between the older mTBI population ($p = 0.0121$) and the young normal group. In contrast, there would be no significant difference between the fatigue effect in the younger vs. older populations of mTBI patients or between the older populations of the two groups.

Figure 6 shows the relation between the fatigue effect (shown as percentage drop in synchronization index) and age in the different subject groups. The synchronization drops from the two normal subjects described above are circled in Fig. 6a; they show a ∼40% loss in synchronization, while the average drop in this group of subjects is $7.23 \pm 15.22\%$.

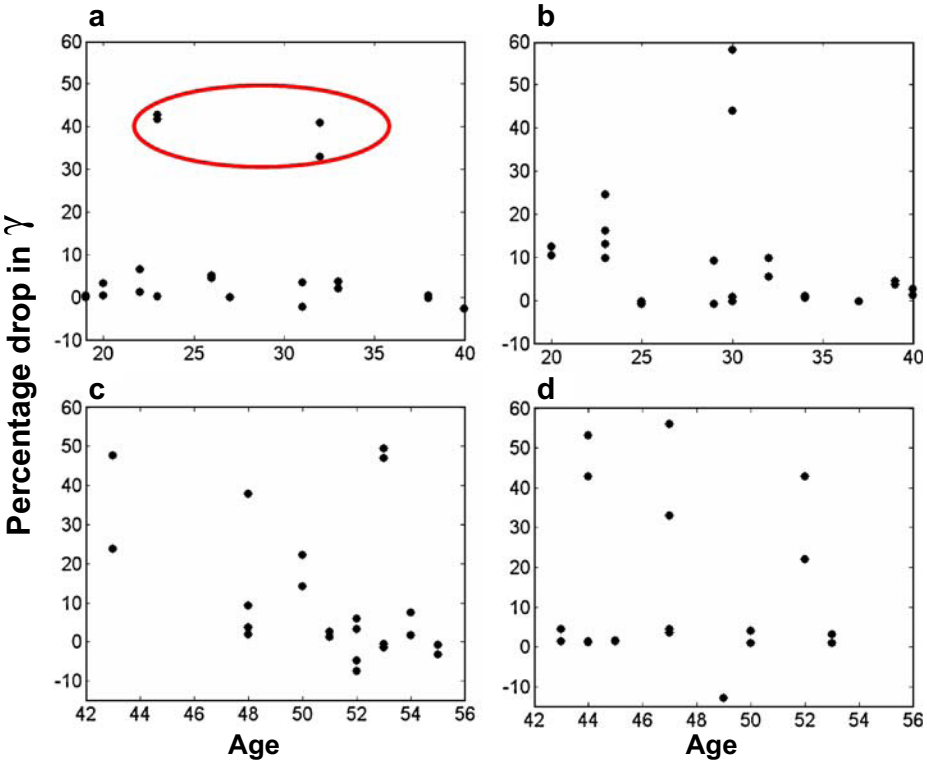

Fig. 6 The percentage drop in synchronization index between the first and second half of each trial is illustrated as a function of age for normal subjects (**a**, young group; **c**, older group) and for TBI patients (**b**, young group; **d**, older group). Note the data from the two "outlier" young normal subjects, *circled* in **a**

4 Discussion

Applying stochastic phase synchronization to SPEM in both normal and mTBI subjects, we find significant fatigue effects in both groups. It should be noted, however, that the observed "fatigue" effect is not necessarily due to actual tiredness in the subjects; indeed, it might be a result of boredom, which has been shown to affect attention [26].

We find that most of the younger normal subjects' ability to synchronize eye movements with a moving target is significantly better than that of older normal subjects. This suggests, even from this small sample size, that age may be a critical factor in the selection of a normal control group against which to compare mTBI patients. Moreover, sensitivity to outliers, seen in the group of younger normal subjects, and the possibility of a conflation of fatigue and boredom effects suggest that a larger sample size and stricter exclusion criteria will be necessary in order to develop a standard for normal SPEM synchronization with which mTBI performance can be compared.

The phase synchronization approach allows the separation of changes in phase from changes in amplitude. Even within phase synchronization techniques, however, various approaches may be taken. The approach chosen here involves calculating the phase with respect to the fixed center of the target circle. Note in Fig. 1b, however, that the circle

traced by the eye can sometimes have a center which is offset from that of the target. While Fig. 1b shows a dramatic example of such offset (at least for this one of many orbits within a longer trial), this raises the question of important subtleties in the calculation of the phase itself. In the present study, we have deliberately chosen the fixed center of the target as our reference for calculating both eye and target phase, since the subject is always cognizant of the location of that point and is instructed to follow a circle with that point at its center. Other approaches could be taken, but they either suffer from extreme variability or address issues beyond the scope of the present study. The first such approach would involve estimating the center of the eye's "circle" as the median eye position during the entire trial. However, due to gradual drift in the eye's circle in some subjects, this might lead to systematic overestimation of synchrony at some intervals during the trial and underestimation during other intervals. An alternative approach would be to separate the x- and y-components of the eye position and to calculate the phase of each of these time series using a Hilbert transform. The synchronization of the x-component with the x-component of the target's motion and that of the y-component with that of the target could be then assessed separately. Indeed, it is known that target tracking in the horizontal direction is more accurate than in the vertical direction [31] and that these two components of eye motion are controlled by different regions in the cerebellum [32]. However, the purpose of the present study was to investigate the phase difference between eye and target using the combined trajectory, rather than to separate the components. For this reason, the Hilbert transform approach is not appropriate for the present study.

The technique of stochastic phase synchronization has been applied to the study of various animal nervous systems, from invertebrates [33, 34] to fish [35]. A model-based deterministic variant of this technique has been applied to SPEM data of normal subjects [36], showing changes in the model parameters over time, which may be explained by fatigue. Stochastic phase synchronization has also been applied to the analysis of pathologies in the human nervous system, as in the development of "synchronization tomography" for the analysis of magnetoencephalography imaging data from human patients with Parkinson's disease [19], as well as for the study of human performance in cognitive tasks [37]. We show that this technique is well suited for the analysis of SPEM in human subjects. The technique is particularly useful in that it offers a means for quickly assessing changes in attention, such as from fatigue and mild TBI, and also does not require the removal of saccades. We suggest that this technique may prove a powerful tool for diagnosing brain injury based on SPEM.

Acknowledgements SB is supported by NSF CAREER Grant no. PHY-0547647; JG and MS are supported by a grant from the James S. McDonnell Foundation to the Brain Trauma Foundation.

References

1. Vanderploeg, R.D., Curtiss, G., Belanger, H.G.: Long-term neuropsychological outcomes following mild traumatic brain injury. J. Int. Neuropsychol. Soc. **11**(3), 228–36 (2005)
2. Dockree, P.M., Bellgrove, M.A., O'Keeffe, F.M., Moloney, P., Aimola, L., Carton, S., Robertson, I.H.: Sustained attention in traumatic brain injury (TBI) and healthy controls: enhanced sensitivity with dual-task load. Exp. Brain Res. **168**(1–2), 218–29 (2006)
3. Stuss, D.T., Pogue, J., Buckle, L., Bondar, J.: Characterization of stability of performance in patients with traumatic brain injury: variability and consistency on reaction time tests. Neuropsychology **8**, 316–324 (1994)

4. Robertson, I.H., Manly, T., Andrade, J., Baddeley, B.T., Yiend, J.: 'Oops!': performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. Neuropsychologia **35**(6), 747–58 (1997)
5. Hetherington, C.R., Stuss, D.T., Finlayson, M.A.: Reaction time and variability 5 and 10 years after traumatic brain injury. Brain Inj. **10**(7), 473–86 (1996)
6. Suh, M., Kolster, R., Sarkar, R., McCandliss, B., Ghajar, J.: Deficits in predictive smooth pursuit after mild traumatic brain injury. Neurosci. Lett. **401**(1–2), 108–13 (2006)
7. Suh, M., Basu, S., Kolster, R., Sarkar, R., McCandliss, B., Ghajar, J.: Increased oculomotor deficits during target blanking as an indicator of mild traumatic brain injury. Neurosci. Lett. **410**(3), 203–7 (2006)
8. Arfanakis, K., Haughton, V.M., Carew, J.D., Rogers, B.P., Dempsey, R.J., Meyerand, M.E.: Diffusion tensor MR imaging in diffuse axonal injury. Am. J. Neuroradiol. **23**, 794–802 (2002)
9. Povlishock, J.T., Katz, D.I.: Update of neuropathology and neurological recovery after traumatic brain injury. J. Head Trauma Rehab. **20**, 75–94 (2005)
10. Gennarelli, T.A., Graham, D.I.: Neuropathology of the head injuries. Semin. Clin. Neuropsychiatry. **3**(3), 160–175 (1998)
11. Smith, D.H., Meaney, D.F., Shull, W.H.: Diffuse axonal injury in head trauma. J. Head Trauma Rehabil. **18**, 307–316 (2003)
12. Kowler, E.: Cognitive expectations, not habits, control anticipatory smooth oculomotor pursuit. Vision Res. **29**, 1049–1057 (1989)
13. Chen, Y., Holzman, P.S., Nakayama, K.: Visual and cognitive control of attention in smooth pursuit. Prog. Brain Res. **140**, 255–265 (2002)
14. Hutton, S.B., Tegally, D.: The effects of dividing attention on smooth pursuit eye tracking. Exp. Brain Res. **163**, 306–313 (2005)
15. Van Donkelaar, P., Drew, A.S.: The allocation of attention during smooth pursuit eye movements. Prog. Brain Res. **140**, 267–77 (2002)
16. Hultsch, D.F., MacDonald, S.W.: Intraindividual variability in performance as a theoretical window onto cognitive aging. In: Dixon, R.A. (ed.) New Frontiers in Cognitive Aging, pp. 65–88. Oxford University Press, Oxford (2004)
17. Takeshita, D., Sato, Y.D., Bahar, S.: Transitions between multistable states as a model of epileptic seizure dynamics. Phys. Rev. E **75**, 051925 (2007)
18. Weihberger, O., Bahar, S.: Frustration, drift, and antiphase coupling in a neural array. Phys. Rev. E **76**, 011910 (2007)
19. Tass, P.A., Fieseler, T., Dammers, J., Dolan, K., Morosan, P., Majtanik, M., Boers, F., Muren, A., Zilles, K., Fink, G.R.: Synchronization tomography: a method for three-dimensional localization of phase synchronized neuronal populations in the human brain using magnetoencephalography. Phys. Rev. Lett. **90**(8), 088101 (2003)
20. Goussard, Y., Martin, B., Stark, L.: A new quantitative indicator of visual fatigue. IEEE Trans. Biomed. Eng. **34**, 23–29 (1987)
21. Porcu, S., Ferrara, M., Urbani, L., Bellatreccia, A., Casagrande, M.: Smooth pursuit and saccadic eye movements as possible indicators of nighttime sleepiness. Physiol. Behav. **65**, 437–443 (1998)
22. De Gennaro, L., Ferrara, M., Urbani, L., Bertini, M.: Oculomotor impairment after 1 night of total sleep deprivation: a dissociation between measures of speed and accuracy. Clin. Neurophysiol. **111**, 1771–1778 (2000)
23. Zils, E., Sprenger, A., Heide, W., Born, J., Gais, S.: Differential effects of sleep deprivation on saccadic eye movements. Sleep **28**, 1109–1115 (2005)
24. Madden, D.J.: Aging and visual attention. Curr. Dir. Psychol. Sci. **16**(2), 70–74 (2007)
25. Cook, D.B., O'Connor, P.J., Lange, G., Steffener, J.: Functional neuroimaging correlates of mental fatigue induced by cognition among chronic fatigue syndrome patients and controls. NeuroImage **36**, 108–122 (2007)
26. Pattyn, N., Neyt, X., Henderickx, D., Soetens, E.: Psychophysical investigation of vigilance decrement: boredom or cognitive fatigue? Physiol. Behav. **93**, 369–378 (2008)
27. Pikovsky, A., Rosenblum, M., Kurths, J.: Synchronization: A Universal Concept in Nonlinear Sciences. Cambridge University Press, Cambridge (2001)
28. Rosenblum, M.G., Pikovsky, A.S., Kurths, J.: Phase synchronization of chaotic oscillators. Phys. Rev. Lett. **76**(11), 1804–1807 (1996)
29. Rosenblum, M.G., Pikovsky, A.S., Kurths, J.: From phase to lag synchronization in coupled chaotic oscillators. Phys. Rev. Lett. **78**(22), 4193–4196 (1997)
30. Rosenblum, M., Pikovsky, A.S., Schäfer, C., Tass, P., Kurths, J.: Phase synchronization: from theory to data analysis (Chapter 9). In: Moss, F., Gielen, S., Hoff, A.J. (eds.) Handbook of Biological Physics: Neuro-informatics, vol. 4, pp. 279–321. Elsevier, Amsterdam (2001)

31. Rottach, K.G., Zivotofsky, A.Z., Das, V.E., Averbuch-Heller, L., Discenna, A.O., Poonyathalang, A., Leigh, R.J.: Comparison of horizontal, vertical and diagonal smooth pursuit eye movements in normal human subjects. Vision Res. **36**(14), 2189–2195 (1996)
32. Schonewille, M., Luo, C., Ruigrok, T.J., Voogd, J., Schmolesky, M.T., Rutteman, M., Hoebeek, F.E., De Jeu, M.T., De Zeeuw, C.I.: Zonal organization of the mouse flocculus: physiology, input, and output. J. Comp. Neurol. **497**(4), 670–82 (2006)
33. Bahar, S., Neiman, A., Wilkens, L.A., Moss, F.: Phase synchronization and stochastic resonance effects in the crayfish caudal photoreceptor. Phys. Rev. E **65**, 050901(R) (2002)
34. Bahar, S.: Effect of light on stochastic phase synchronization in the crayfish caudal photoreceptor. Biol. Cybern. **89**(3), 200–213 (2003)
35. Neiman, A.B., Russell, D.F.: Synchronization of noise-induced bursts in noncoupled sensory neurons. Phys. Rev. Lett. **88**(13), 138103 (2002)
36. Voss, H.U., McCandliss, B.D., Ghajar, J., Suh, M.: A quantitative synchronization model for smooth pursuit target tracking. Biol. Cybern. **96**, 309–322 (2007)
37. Rodriguez, E., George, N., Lachaux, J.-P., Martinerie, J., Renault, B., Varela, F.J.: Perception's shadow: long distance synchronization of human brain activity. Nature **397**, 430–433 (1999)