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Smooth Pursuit Eye Movement Deficits in Patients With Whiplash and Neck Pain are Modulated by Target Predictability

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Study Design. This is a cross-sectional study.

Objective. The purpose of this study is to support and extend previous observations on oculomotor disturbances in patients with neck pain and whiplash-associated disorders (WADs) by systematically investigating the effect of static neck torsion on smooth pursuit in response to both predictably and unpredictably moving targets using video-oculography.

Summary of Background Data. Previous studies showed that in patients with neck complaints, for instance due to WAD, extreme static neck torsion deteriorates smooth pursuit eye movements in response to predictably moving targets compared with healthy controls.

Methods. Eye movements in response to a smoothly moving target were recorded with video-oculography in a heterogeneous group of 55 patients with neck pain (including 11 patients with WAD) and 20 healthy controls. Smooth pursuit performance was determined while the trunk was fixed in 7 static rotations relative to the head (from 45° to the left to 45° to right), using both predictably and unpredictably moving stimuli.

Results. Patients had reduced smooth pursuit gains and smooth pursuit gain decreased due to neck torsion. Healthy controls showed higher gains for predictably moving targets compared with unpredictably moving targets, whereas patients with neck pain had similar gains in response to both types of target movements. In 11 patients with WAD, increased neck torsion decreased smooth pursuit performance, but only for predictably moving targets.

Conclusion. Smooth pursuit of patients with neck pain is affected. The previously reported WAD-specific decline in smooth pursuit due to increased neck torsion seems to be modulated by the predictability of the movement of the target. The observed oculomotor disturbances in patients with WAD are therefore unlikely to be induced by impaired neck proprioception alone.

Key words: smooth pursuit, whiplash, neck pain, neck torsion, stimulus predictability, human, eye movements, diagnostic test, video-oculography, proprioception.

Level of Evidence: 3

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Patients with neck pain often present with headaches, dizziness, as well as visual problems,[1,2] which can be related to problems in eye movement control.[3–6] This includes smooth pursuit, which is an eye movement that is executed to keep track of a moving object.[7] The Smooth Pursuit Neck Torsion (SPNT) test is a clinical test that has been developed to diagnose patients with cervical dizziness (reported sensitivity/specificity: 90%/91%).[4] This test is based on the observed decrease in smooth pursuit performance in patients due to static neck torsion (placing the head in rotated position while keeping the trunk stationary). Smooth pursuit performance is reflected by the smooth pursuit gain, that is, the velocity of the eye movement relative to the velocity of the moving object. A gain of 1 implies perfect smooth pursuit. A decline in smooth pursuit performance with increased neck torsion was not observed in healthy controls. A later study validated the SPNT for diagnosing patients with whiplash-associated disorder (WAD), and reported high diagnostic value in discriminating these patients from others with cervical complaints.[8] Additional studies that used the SPNT reproduced these findings of gain decline and specificity for patients with WAD.[9,10] However, several factors impede proper assessment of these findings. First, subjects were fixated manually, which reduces the comparison and reproducibility between measurements because one cannot make sure that the same neck torsion is applied at all times. Second, eye movement recordings were commonly done by means of electrooculography, which is quite unreliable to detect small changes

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in eye position as well as relatively slow eye movements.[11] Finally, a limited variety of neck torsions was usually applied (either none or very prominent, that is, about 45° of head rotation relative to the body). A final important limitation is related to the predictable motion of the object used to evoke smooth pursuit. With such a predictable motion, the sought-for modifications in smooth pursuit behavior might be compensated for by adequate prediction of target motion.[7,12–15] This confounding factor can be avoided by using an unpredictably moving target.

In this research, we studied the effects of neck torsion and target predictability on smooth pursuit eye movement in patients with various origins of neck pain, avoiding the issues mentioned above. We expect that increased neck torsion would have more detrimental effects on smooth pursuit performance in patients than in healthy controls. Furthermore, we hypothesized an interaction between target predictability and neck torsion, with the SPNT with unpredictably moving targets being more affected.

MATERIALS AND METHODS

Subjects

20 healthy controls and 55 patients with neck pain participated in this experiment. Healthy controls were recruited among the hospital and university staff: they formed a heterogeneous group of 10 males and 10 females, being on average 28.4 years old (range 20–51 yr). None of the control subjects had a history of trauma, neck complaints, or neurological conditions. All had normal or corrected to normal vision. Importantly, none of the controls had experienced severe neck pain in the last 6 months.

For the patients, we looked at a heterogeneous group with various origins of their complaints, both traumatic and nontraumatic. Patients were included with support of the Spine and Joint Centre Rotterdam, a rehabilitation center for patients with chronic neck complaints, as well as regular physical therapists. In total, 55 patients (21 males, 34 females, mean age 44.2 yr, range 25–67 yr) were included. All patients experienced chronic pain in the neck for more than 6 months that impaired their behavior in daily life. The patients were diagnosed as having WAD (n = 11) or not (non-WAD, n = 44) according to experienced physicians of the Spine and Joint Centre Rotterdam, with the use of the criteria of Spitzer.[16]

All participants gave informed consent and the study was approved by the local review board.

Apparatus

The methodology has been described in detail elsewhere.[17] Briefly, subjects were seated in a custom-made rotatable chair. Rotating the chair to a fixed position, while keeping the head pointing straight ahead induced static neck torsion. Eye movements in response to a moving red dot on a black background were recorded by means of video-oculography (resolution noise <0.01°, velocity noise <3°/s, sample rate 250 Hz).[18]

Experiment

7 chair rotations were used: a neutral rotation (0° straight ahead, *i.e.*, the head and trunk were aligned) and a rotation of 15°, 30°, 45° to the left or to the right (Figure 1). The experiment consisted of 9 runs in which the chair was positioned in a specific rotation. Each eccentric rotation was applied once and the neutral rotation was applied 3 times. In each run, conditions were applied.

There were 2 conditions in this experiment: a predictable motion condition and an unpredictable motion condition. In the predictable condition, the target moved according to a single sinusoid with frequency of 0.4 Hz and a peak-to-peak amplitude of 27°. In the unpredictable condition, the target moved according to a sum of 3 sinusoids with different frequencies and amplitudes. One of the sinusoids had a frequency of 0.4 Hz and a peak-to-peak amplitude of 27°, like the predictably moving target. 3 unpredictable stimuli were used randomly between runs to prevent learning. In each run, the predictable condition was performed first, followed by the unpredictable condition. Both conditions lasted about 33 seconds.

Procedure

The order of the 7 chair rotations was pseudo-randomized across subjects. Neutral rotation was measured 3 times at the 1st, 5th, and 9th run. The experiment lasted about 20 minutes.

Analysis

The recorded eye data were parsed for events (blinks, saccades, and fixations) and eye positions using the built-in

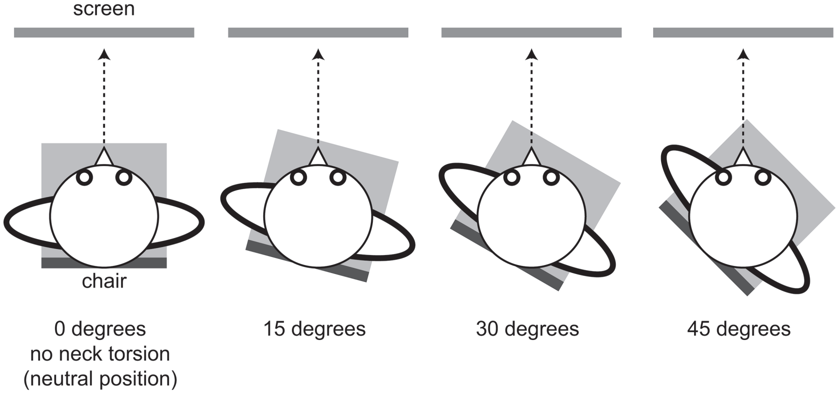

Figure 1. Schematic representation of the chair rotation conditions. While the head was fixated by means of a bite board, the torso was held in a fixed rotation to the right or to the left, which induced static neck torsion. The subject was asked to follow a single moving dot that was projected on the screen in front.

EyeLink software (EyeLink II, SR Research Ltd., Ottawa, ON, Canada), and subsequently analyzed off-line using custom-written software in MatLab (Release 2008b, The MathWorks, Inc., Natick, MA).

Instantaneous eye velocity signals were calculated from the eye position signals. The numbers of saccadic intrusions (amplitude >1.0°) were counted in a time window of 30 seconds, starting 1 second after the commencement of recording. Saccades and square waves, as well as eye blinks, were removed from the velocity signals. For the predictable condition, a sinusoid with a frequency of 0.4 Hz was fitted through the eye velocity data. This yielded a gain of the smooth pursuit eye movement. The gain was defined as the fitted eye velocity amplitude divided by the target velocity amplitude (fixed at $2 \times \pi \times 0.4 \times 13.5 = 33.9$°/s). For the unpredictable condition, a sum of 3 sinusoids, with frequencies matching the 3 target frequencies, was fitted through the eye velocity data. These combinations were 0.4 Hz combined with 1 of 3 frequency pairs (0.182 and 0.618 Hz, 0.222 and 0.578 Hz, or 0.268 and 0.532 Hz), which were on average all 0.4 Hz. This yielded 3 fitted eye velocity amplitudes. The gain of the unpredictable smooth pursuit eye movement was defined as the fitted amplitude for 0.4 Hz divided by the target velocity amplitude at 0.4 Hz (fixed at $2 \times \pi \times 0.4 \times 13.5 = 33.9$°/s).

The number of saccadic intrusions was determined because an increased number of saccades during smooth pursuit eye movement is associated with worse performance.[19,20] The gains and the number of saccadic intrusions of the 2nd and 3rd measurement at neutral position, were averaged, to obtain values for this chair rotation (the first measurement in this rotation was discarded). Data for each chair rotation eccentricity to the left and to the right were combined by taking the average of the 2 values, because a preliminary analysis showed no effect of the direction of chair rotation.

Statistical analyses were performed using all the complete measurements by means of repeated measurements ANOVAs, which included 1 between-subject factor "Group" with 2 levels (patients *vs.* controls) and 2 within-subject factors ("Neck Torsion" with 4 levels: 0°, 15°, 30°, and 45° of chair rotation; "Predictability" with 2 levels: predictable *vs.* unpredictable smooth pursuit target motion). For both outcome parameters (gain and number of saccadic intrusions), a separate ANOVA was performed. Correlations between the smooth pursuit gain and the number of saccadic intrusions were assessed using Pearson correlation coefficient.

For each subject, we also calculated the SPNT difference, similar to the previous studies.[4,8,21] The SPNT difference is defined as the difference between the average gain in the neutral position and the gain in the most eccentric measured positions, averaged over left and right. In most cases, this was the 45° torsion. The SPNT difference was analyzed using a repeated measurement ANOVA with 1 between-subject factor "Group" with 2 levels (patients *vs.* controls) and 1 within-subject factor ("Predictability" with 2 levels: predictable *vs.* unpredictable moving targets). We also analyzed the groups of patients with neck pain (WAD and non-WAD) separately.

RESULTS

Study Population

In total 55 patients with neck pain were included. The data of 1 patient were discarded due to eye movement recording problems. 45 patients (including 7 patients with WAD) were measured in all 7 chair rotations.

The other 9 patients provided only a partial dataset. 5 patients could not reach 45° neck torsion and measurements at these eccentricities were skipped. Another 4 patients could not complete the measurements due to complaints of fatigue or too much pain and only the first 3 measurements (0°, 45° to the left and to the right) were performed. However, the partial data of these 9 patients could be included in the analysis of the SPNT difference.

The experiment was performed successfully in all 20 controls. Their results have been reported in more detail previously.[17]

Smooth Pursuit Gains

Smooth pursuit gains of patients and controls are shown in Figure 2. The overall ANOVA showed that the 20 healthy controls had higher smooth pursuit gains (0.90 ± 0.03) than 45 patients with neck pain (0.76 ± 0.02, $F(3,62) = 18.12$, $P < 0.00$, partial $\eta^2 = 0.22$). A significant main effect of Neck Torsion on smooth pursuit gain ($F(3,62) = 2.80$, $P = 0.05$, partial $\eta^2 = 0.12$) showed that gains decreased a little with increasing neck torsion (0.84 ± 0.02, 0.84 ± 0.02, 0.84 ± 0.02, and 0.82 ± 0.02, for 0°, 15°, 30°, and 45°, respectively). No interaction between Neck Torsion and Predictability was observed ($P = 0.10$). The interaction between Neck Torsion and Group failed to reach significance ($P = 0.06$).

Predictability affected smooth pursuit gain significantly ($F(1,64) = 4.36$, $P = 0.04$, partial $\eta^2 = 0.06$): gains for predictably moving targets were higher than for unpredictably moving targets (0.85 ± 0.02 *vs.* 0.82 ± 0.02, respectively). Predictability showed a significant interaction with Group ($F(1,64) = 4.48$, $P = 0.04$, partial $\eta^2 = 0.07$): healthy controls

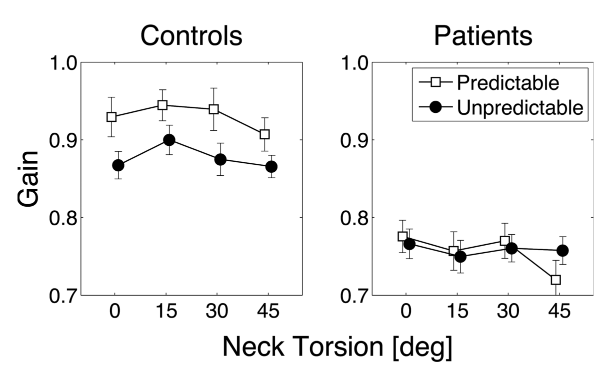

Figure 2. Smooth pursuit gains per group (20 controls and 45 patients), for each of the 4 eccentricities of chair rotation (Neck Torsion), and for predictably moving targets (open squares) and unpredictably moving targets (closed circles). Error bars represent standard error of the mean.

had a higher gain for predictably moving targets (0.93 ± 0.03) than for unpredictably moving targets (0.88 ± 0.03, $P < 0.00$), whereas patients had similar gains in both conditions (0.76 ± 0.03 *vs.* 0.76 ± 0.02, respectively, $P = 0.98$). The interaction involving all 3 factors was not significant ($P = 0.63$).

The ANOVA performed on the number of saccadic intrusions showed no effect of Group ($P = 0.11$) and none of the interactions involving Group reached significance (all $P >$ 0.30). We did observe a small effect of Neck Torsion ($F(3,54) = 3.03$, $P = 0.04$, partial $\eta^2 = 0.14$): more eccentric positions evoked slightly more saccadic intrusions (70.5 ± 2.1, 71.2 ± 2.5, 73.6 ± 2.5, and 73.9 ± 2.1 saccadic intrusions, for 0°, 15°, 30°, and 45° neck torsion, respectively). We also observed a small effect of Predictability on the number of saccadic intrusions ($F(1,56) = 15.32$, $P < 0.00$, partial $\eta^2 = 0.22$), with unpredictably moving targets evoking fewer saccadic intrusions (69.5 ± 1.9) than predictably moving targets (75.6 ± 2.5). The interaction between Neck Torsion and Predictability was weak, but just significant ($F(3,54) = 3.00$, $P = 0.04$, partial $\eta^2 = 0.14$). The number of saccadic intrusions increased slightly more with neck torsion for predictably moving targets (73.0–78.1 intrusions, at 0° and 45° chair rotation, respectively) than for unpredictably moving targets (67.9–69.8 intrusions).

There was no correlation between the smooth pursuit gain and the number of saccadic intrusions in controls ($r^2 = 0.014$, $P = 0.62$) or in patients ($r^2 = 0.06$, $P = 0.72$) in the neutral condition.

SPNT Difference

The SPNT difference could be calculated for all 20 controls and 54 patients, thereby including those patients who skipped measurements at certain chair rotations. The SPNT difference was calculated using a chair rotation of 30° in 5 patients, and the maximum chair rotation of 45° in 49 patients.

We first compared all patients to controls. Analysis showed no main effect of Group ($F(1) = 0.73$, $P = 0.40$, partial $\eta^2 = 0.01$). The SPNT difference was higher for predictably moving targets than for unpredictably moving targets (−0.04 ± 0.01 *vs.* −0.01 ± 0.01, respectively, $F(1) = 5.39$, $P = 0.02$, partial $\eta^2 = 0.07$). There was no interaction between Group and Predictability ($P = 0.38$).

We also looked at the effect of target predictability on the SPNT difference in healthy controls, in patients with WAD, and in non-WAD patients separately (Figure 3). In healthy controls and in non-WAD patients, the SPNT difference was not significantly different between predictably and unpredictably moving targets (controls: −0.02 ± 0.07 *vs.* −0.00 ± 0.07, respectively, $t(19) = -1.27$, $P = 0.22$; non-WAD patients: −0.05 ± 0.11 *vs.* −0.01 ± 0.12, respectively, $t(42) = 1.77$, $P = 0.09$). In patients with WAD, however, the SPNT difference was larger for predictably than for unpredictably moving targets (−0.08 ± 0.12 *vs.* 0.01 ± 0.05, respectively, $t(10) = 3.21$, $P = 0.01$).

Comparisons between the 3 groups for predictably and unpredictably moving targets separately showed that the SPNT differences in patients with WAD did not differ from that of controls or non-WAD patients (all $P > 0.12$).

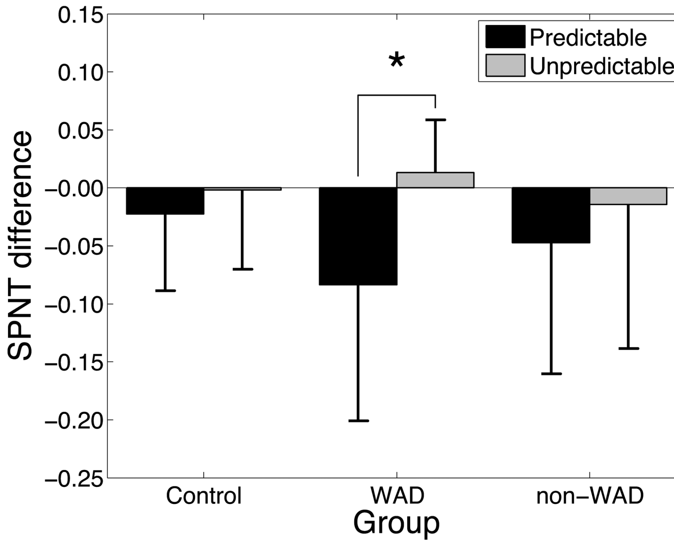

Figure 3. Smooth Pursuit Neck Torsion (SPNT) differences for each of the 3 groups (controls, patients with WAD, and non-WAD patients) and the 2 stimulus conditions (predictably moving targets and unpredictably moving targets). Error bars represent standard deviations. *$P <$ 0.05. WAD indicates whiplash-associated disorder.

DISCUSSION

We investigated the effect of neck torsion and target predictability on smooth pursuit eye movements in patients with neck pain. As expected based on previous reports, patients with neck pain showed lower smooth pursuit gains than healthy controls.[4,8–10,21,22] Moreover, smooth pursuit gains in patients decreased with increasing torsion of the neck, which is in line with several previous studies.[4,8–10] However, this decrease in gain was not different between patients and controls. This finding was supported by the analysis according to SPNT test. The differences in smooth pursuit gains between most eccentric neck rotations and neutral rotations were the same in patients with neck pain as in controls.

Target predictability, however, affected smooth pursuit gains differently in healthy controls and patients. In line with previous studies using predictably moving stimuli, we observed the performance of patients with neck pain was impaired compared with healthy controls.[4,8–10,21,22] However, smooth pursuit performance of healthy controls decreased when targets moved unpredictably, which might be explained by the fact that these subjects are adequately able to predict the movement of the target when the target moved in a simple fashion.[23,24] In contrast, the performance of patients with neck pain was the same for both conditions. This novel finding could suggest that the constant pain in their neck already hampered adequate prediction of the straightforward trajectory of a target. A similar hypothesis was put forward by Prushansky *et al*,[23] who suggested that observed deficits in eye movement performance in patients with WAD were related to pain. Another explanation is that patients with neck pain are too distracted by the pain in their neck to perform optimally when the task is less challenging. In this respect, it is worth to note that some patients spontaneously mentioned they found it hard to keep focused when the target moved predictably. This lack of focus could explain the lower gains for the predictably moving targets. Future studies in patients with neck pain might incorporate tests of concentration and attention to assess their effects on smooth pursuit performance. Moreover, to correlate pain experience with performance, a detailed analysis of pain experience might be fruitful.

We also aimed to differentiate between patients with whiplash (WAD) and non-WAD. In accordance with previous reports, we observed that for predictably moving targets the SPNT difference was larger in patients with WAD than in controls and non-WAD patients.[8–10,21] In our population, this difference was not significant, probably due to a lack of power. However, the SPNT differences disappeared completely when we used unpredictably moving targets. The observation that in patients with WAD the SPNT difference is altered to a large extent by target predictability, raises the question whether the observed effect of increased neck torsion on smooth pursuit performance is due to eye movement deficits alone, as suggested by previous research.[25] If this was the case, increased neck torsion in patients with WAD would also lead to lower gains for unpredictably moving targets. This was not observed. Therefore, the reduced gains for predictably moving targets induced by increased neck torsion could well be caused by confounding factors such as pain experience or impaired cognitive functioning (*e.g.*, attention). This explanation is supported by previous observations showing that patients with WAD have normal reflexive saccadic eye movements, but impaired voluntary ones, which was explained by the authors as being caused by (pre-)frontal dysfunction.[26]

A strength of the present study was the use of a high-quality video-oculography to record smooth pursuit eye movements and the range of applied neck torsions from extreme left to extreme right. A limitation is the relatively small number of subjects in the 2 patient groups. Moreover, not all patients could be measured in all chair rotation eccentricities. Therefore, too few subjects remained to make the favorable separation into 2 patient groups in the overall ANOVA. On the other hand, all patients could be included in the SPNT test. Furthermore, groups differed in age and because eye movements are altered when getting older, a more even age distribution would be recommended for future studies.[27–29]

In conclusion, the differential effects of neck torsion in patients with WAD, non-WAD patients, and controls on smooth pursuit performance seem to be modulated by the predictability of the target trajectory. The observed oculomotor disturbances in patients with WAD are therefore unlikely to be induced by impaired neck proprioception alone. Future studies investigating the relationship between impaired neck proprioception and eye movement control could take this property of the visual stimulus into account.

➢ Key Points

- ❑ Smooth pursuit performance is degraded in patients with neck pain.
- ❑ Smooth performance is affected by target predictability in healthy controls, but not in patients with neck pain.
- ❑ The previously reported WAD-specific decline in smooth pursuit due to increased neck torsion is only seen when the target moves predictably.

References

1. Treleaven J, Takasaki H. Characteristics of visual disturbances reported by subjects with neck pain. *Man Ther* 2014;19:203–7.
2. Leaver AM, Maher CG, McAuley JH, et al. Characteristics of a new episode of neck pain. *Man Ther* 2013;18:254–7.
3. Kelders W, Kleinrensink G, Van Der Geest J, et al. The cervico-ocular reflex is increased in whiplash injury patients. *J Neurotrauma* 2005;22:133–7.
4. Tjell C, Rosenhall U. Smooth pursuit neck torsion test: a specific test for cervical dizziness. *Am J Otol* 1998;19:76–81.
5. Treleaven J, Jull G, Grip H. Head eye co-ordination and gaze stability in subjects with persistent whiplash associated disorders. *Man Ther* 2011;16:252–7.
6. Storaci R, Manelli A, Schiavone N, et al. Whiplash injury and oculomotor dysfunctions: clinical–posturographic correlations. *Eur Spine J* 2006;15:1811–6.
7. Barnes G, Collins C. Internally generated smooth eye movement: its dynamic characteristics and role in randomised and predictable pursuit. *Prog Brain Res* 2008;171:441–9.
8. Tjell C, Tenenbaum A, Sandström S. Smooth pursuit neck torsion test-a specific test for whiplash associated disorders? *J Whiplash Relat Disord* 2002;1:9–24.
9. Treleaven J, Jull G, LowChoy N. The relationship of cervical joint position error to balance and eye movement disturbances in persistent whiplash. *Man Ther* 2006;11:99–106.
10. Treleaven J, LowChoy N, Darnell R, et al. Comparison of sensorimotor disturbance between subjects with persistent whiplash-associated disorder and subjects with vestibular pathology associated with acoustic neuroma. *Arch Phys Med Rehabil* 2008;89:522–30.
11. Hess C, Muri R, Meienberg O. Recording of horizontal saccadic eye movements: methodological comparison between electro-oculography and infrared reflection oculography. *Neuro Ophthalmol* 1986;6:189–97.
12. Barnes G, Asselman P. The mechanism of prediction in human smooth pursuit eye movements. *J Physiol* 1991;439:439–61.
13. Barnes GR. Cognitive processes involved in smooth pursuit eye movements. *Brain Cogn* 2008;68:309–26.
14. Matsuoka K, Ueda Y. Frequency characteristics of the smooth pursuit component in tracking eye movements. *Ergonomics* 1986;29:197–214.
15. Soechting J, Rao H, Juveli J. Incorporating prediction in models for two-dimensional smooth pursuit. *PLoS ONE* 2010;5:e12574.
16. Spitzer W, Skovron M, Salmi L, et al. Scientific monograph of the quebec task force on Whiplash-associated disorders: Redefining “whiplash” and its management. *Spine (Phila Pa 1976)* 1995;20:1S–73S.
17. Janssen M, Vries J, Ischebeck B, et al. Small effects of neck torsion on healthy human voluntary eye movements. *Eur J Appl Physiol* 2013;113:3049–57.
18. Geest van der J, Frens M. Recording eye movements with video-oculography and scleral search coils: a direct comparison of two methods. *J Neurosci Methods* 2002;114:185–95.

19. Karoumi Bb, Saoud M, d'Amato T, et al. Poor performance in smooth pursuit and antisaccadic eye-movement tasks in healthy siblings of patients with schizophrenia. *Psychiatry Res* 2001;101:209–19.
20. Clementz BA, Sweeney JA, Hirt M, et al. Pursuit gain and saccadic intrusions in first-degree relatives of probands with schizophrenia. *J Abnorm Psychol* 1990;99:327–35.
21. Treleaven J, Jull G, LowChoy N, et al. Smooth pursuit neck torsion test in whiplash-associated disorders: relationship to self-reports of neck pain and disability, dizziness and anxiety. *J Rehabil Med* 2005;37:219–23.
22. Della Casa E, Affolter Helbling J, Meichtry A, et al. Head-eye movement control tests in patients with chronic neck pain; inter-observer reliability and discriminative validity. *BMC Musculoskelet Disord* 2014;15:11.
23. Prushansky T, Dvir Z, Pevzner E, et al. Electro-oculographic measures in patients with chronic whiplash and healthy subjects: a comparative study. *J Neurol Neurosurg Psychiatry* 2004;75:1642–4.
24. Kongsted A, Jørgensen L, Leboeuf-Yde C, et al. Are altered smooth pursuit eye movements related to chronic pain and disability following whiplash injuries? A prospective trial with one-year follow-up. *Clin Rehabil* 2008;22:469–79.
25. Paige GD. Senescence of human visual-vestibular interactions: smooth pursuit, optokinetic, and vestibular control of eye movements with aging. *Exp Brain Res* 1994;98:355–72.
26. Mosimann UP, Müri RM, Felblinger J, et al. Saccadic eye movement disturbances in whiplash patients with persistent complaints. *Brain* 2000;123:828–35.
27. Pelak V. Ocular motility of aging and dementia. *Curr Neurol Neurosci Rep* 2010;10:440–7.
28. Kelders W, Kleinrensink G, van der Geest J, et al. Compensatory increase of the cervico-ocular reflex with age in healthy humans. *J Physiol* 2003;553:311–7.
29. Munoz D, Broughton J, Goldring J, et al. Age-related performance of human subjects on saccadic eye movement tasks. *Exp Brain Res* 1998;121:391–400.