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Small effects of neck torsion on healthy human voluntary eye movements

M. Janssen · J. de Vries · B. K. Ischebeck · M. A. Frens · J. N. van der Geest

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Abstract
Purpose Although several lines of research suggest that the head and eye movement systems interact, previous studies have reported that applying static neck torsion does not affect smooth pursuit eye movements in healthy controls. This might be due to several methodological issues. Here we systematically investigated the effect of static neck torsion on smooth pursuit and saccadic eye movement behavior in healthy subjects.
Methods In twenty healthy controls, we recorded eye movements with video-oculography while their trunk was in static rotation relative to the head (7 positions from 45° to the left to 45° to right). The subject looked at a moving dot on the screen. In two separate paradigms, we evoked saccadic and smooth pursuit eye movements, using both predictable and unpredictable target motions.
Results Smooth pursuit gain and saccade peak velocity decreased slightly with increasing neck torsion. Smooth pursuit gains were higher for predictable target movements than for unpredictable target movements. Saccades to predictable targets had lower latencies, but reduced gains compared to saccades to unpredictable targets. No interactions between neck torsion and target predictability were observed.
Conclusion Applying static neck torsion has small effects on voluntary eye movements in healthy subjects. These effects are not modulated by target predictability.

Keywords Smooth pursuit eye movement · Saccadic eye movement · Proprioception · Neck torsion · Human

Introduction

Humans can shift their gaze voluntarily for optimal visual processing. New objects can be viewed by executing saccadic eye movements that rapidly redirect the line of sight, while moving objects can be followed using smooth pursuit eye movement. In daily life, these eye movements occur together with head movements, to ensure that gaze shifts are fast, accurate and efficient. It is not surprising that several lines of research suggest that the head movement system and the eye movement system interact (Corneil et al. 2010; Treleaven et al. 2008).

Electrical stimulation of the frontal eye fields in monkeys evokes a saccadic eye movement (Bruce et al. 1985). However, it also results in contraction of neck muscles that yield head movement in the same direction as the saccade, even when the stimulation is at subthreshold level and no saccade is executed (Corneil et al. 2010). A similar finding has been observed for the supplementary eye fields (Chapman et al. 2012). Electrophysiological recordings from eye movement structures, like the frontal eye fields (Fukushima et al. 2010) and the superior colliculus (an

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M. Janssen · J. de Vries · B. K. Ischebeck · M. A. Frens · J. N. van der Geest (✉)
Department of Neuroscience, Erasmus MC, PO Box 2040, 3000 CA Rotterdam, The Netherlands
e-mail: j.vandergeest@erasmusmc.nl

J. de Vries
Department of Manual Therapy, Hogeschool Rotterdam, Rotterdam, The Netherlands

B. K. Ischebeck
Spine and Joint Centre, Rotterdam, The Netherlands

M. A. Frens
Erasmus University College, Rotterdam, The Netherlands

important area for eye head co-ordination) (Corneil et al. 2008), show that some cells in these areas modulate their responses based on altered cervical afferent input due to changes in head position. Some clinical studies have reported affected smooth pursuit gains following static rotation of the head relative to the body in patients with neck pain due to, for instance, whiplash-associated disorder (Tjell et al. 2002; Treleaven et al. 2008, but also see Prushansky et al. 2004) or cervical spondylosis (Gabr and Emara 2010). These findings underlie the smooth pursuit neck torsion (SPNT) test used to assess the degree of eye movement impairments relating to clinical neck pain populations (Tjell and Rosenhall 1998).

In healthy subjects, on the other hand, neck torsion seems to affect eye movements minimally at most (Treleaven et al. 2005, 2008; Tjell and Rosenhall 1998). Although this is usually welcomed in clinical practice, as it increases the discriminative ability of the SPNT, the lack of neck torsion effects in non-patient populations might be the result of reduced sensitivity due to various methodological issues. Firstly, most of these clinical studies focused on smooth pursuit eye movements and less so on saccadic eye movements. Secondly, smooth pursuit eye movements were evoked by a predictably moving target. Therefore, any decline in smooth pursuit performance due to changes in low-level motor processes might well be compensated for by higher-level cognitive processes that predict target motion (Barnes and Collins 1987, 2008; Matsuoka and Ueda 1986). Thirdly, only a few neck rotations are applied in the SPNT, with one extreme (30 or 45° to the left or right) and one neutral (straight ahead) rotation. Moreover, neck rotation was usually enforced by holding the head manually. Fourthly, eye movements were recorded by means of electro-oculography (EOG) which is known to be limited in its accuracy and reliability (Hess et al. 1986; Collewijn 1999). Although an influence of neck torsion on eye movements in healthy subjects is expected given the alleged interaction between head and eye movement systems, these methodological issues might hamper observing such an effect.

In the present study, we measured eye movements by means of video-oculography and systematically investigated the effect of neck torsion on both smooth pursuit and saccadic eye movements. We displayed targets with predictable and unpredictable movements and used a custom-made bite board to fixate the head while applying a range of static rotations to the trunk. We hypothesized that increased neck torsion would yield small changes in eye movement characteristics which are more pronounced for unpredictably moving targets than for predictably moving targets. In addition, we expect that unpredictably moving targets would yield less optimal eye movements, showing longer saccadic latencies and reduced gains.

Methods

Subjects

Twenty healthy subjects participated in each of the two experimental paradigms (smooth pursuit eye movements and saccadic eye movements); 16 subjects participated in both paradigms. None of the subjects had a history of trauma, neck complaints or neurological conditions. In all subjects, vision was normal or corrected to normal. In the smooth pursuit paradigm, subjects (10 male, 10 female) were on average 28.4 years old (range 20–51 years); in the saccade paradigm, subjects (9 male, 11 female) were on average 27.9 years old (range 21–44 years). All subjects gave informed consent to participate in this study, which was approved by the local ethical board.

Apparatus

The paradigms were performed in a darkened and quiet room. Subjects were seated in a custom-made rotatable chair. Body movements were restricted by seat belts. Head movements were restrained by means of a bite board. Rotating the chair to a fixed position, while keeping the head pointing straight ahead, induced static neck torsion.

Visual stimuli were generated in Matlab (version 2008) and back-projected by a projector (Infocus LP 335) on a translucent screen, placed 168 cm in front of the subject. In both the saccade and smooth pursuit paradigm, the visual target was a single red dot of 0.5° of visual angle in diameter that was displayed on a black background. We will refer to this dot as the target.

Eye movements were measured at 250 Hz with an infrared eye-tracking device (Eyelink I, SMI, Germany, see van der Geest and Frens 2002).

Paradigms

Subjects participated in two experimental paradigms: saccades and smooth pursuit. Each paradigm consisted of multiple runs. In both paradigms and in each run, the chair was rotated to one out of seven positions to induce static neck torsion, i.e., the trunk was rotated while the head was kept pointing straight ahead (Fig. 1a). These seven chair rotations were 15, 30 and 45° to the left or to the right and a neutral rotation (0° straight ahead, i.e., the head and trunk were aligned).

In the *saccade paradigm*, subjects were instructed to look at the target while it jumped on the screen (Fig. 1b). At the beginning of a trial, the target was presented at the center of the screen. After a random interval of 0.8–1.6 s, the target disappeared and immediately appeared unpredictably at one out of six possible locations. These locations

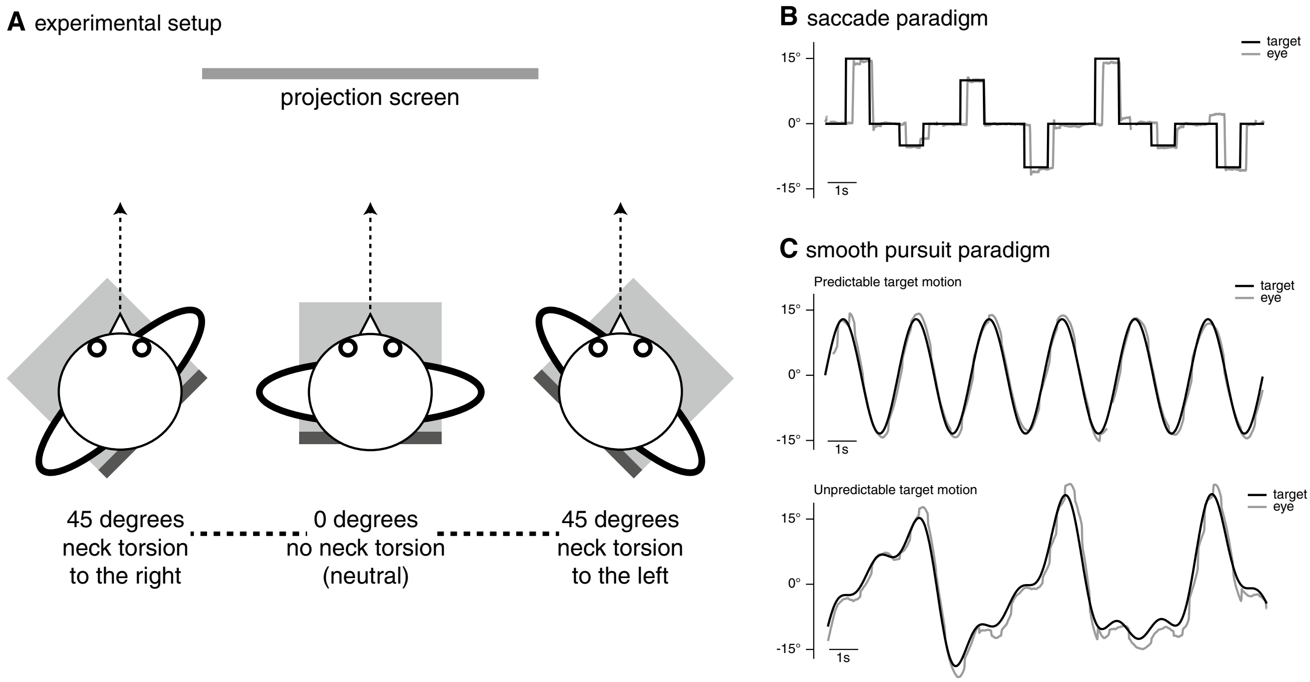

Fig. 1 Experimental setup and paradigms. **a** A schematic representation of the experimental setup: the body of the subjects was rotated to a static position while the head faced forward toward the screen on which the target was presented. **b** An example of the saccade paradigm: eye movement responses (*gray line*) in response to a target (*black line*) that jumped from the center to a peripheral position and back again. **c** Examples of the smooth pursuit paradigm: eye movement responses (*gray line*) in response to a predictably (*top*) or unpredictably (*bottom*) moving smooth pursuit target (*black line*)

were 5, 10 or 15° of visual angle to the left or right site from the center. After a random interval of 0.8–1.6 s, the target disappeared from that location and immediately appeared at the center of the screen, indicating the beginning of the next trial. In each trial, two saccades were therefore evoked. The first centrifugal saccade was directed to an unpredictable position, whereas the second saccade was always directed toward the center (centripetal) and therefore was predictable with respect to its direction and amplitude. We note that target predictability is confounded with the initial eye position, but this is unlikely to have a significant impact (see "Discussion"). Each of the six possible locations was used in ten trials, yielding 120 trials in total per run. The duration of the target display and the order of used target locations were randomized in each run. A run lasted about 2 min.

In the *smooth pursuit paradigm*, subjects were instructed to look at the target while it moved gradually from left to right on the screen in the horizontal plane (Fig. 1c). There were two conditions in this paradigm: 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 three sinusoids with different frequencies and amplitudes (Sum of Sines stimulation, Soechting et al. 2010). One of the sinusoids had a frequency of 0.4 Hz and a peak to peak amplitude of 27°, like the predictably moving target. In a single run, the other two (non-harmonic) sinusoids were one of the following pairs: 0.182 and 0.618 Hz, 0.222 and 0.578 Hz or 0.268 and 0.532 Hz. Note that for each combination, the average frequency was 0.4 Hz. Three different combinations were used randomly between runs to prevent learning. In each run, the predictable condition was performed first for about 30 s, followed by the unpredictable condition for about 30 s. In between conditions was a brief pause of about 5 s. A run lasted a little over 1 min.

Procedure

The order of the chair rotations was pseudo-randomized across subjects. In the first run, the chair was in neutral rotation (0°), followed by a 45° chair rotation either to the left or the right in the second run. In the third run, the chair was rotated 45° to the other direction. In the following runs, the four remaining rotations were applied in a pseudo-random order across subjects. In the smooth pursuit paradigm only, an additional measurement was made with neutral chair rotation in the fourth run. In both paradigms, a neutral chair rotation (0°) was used for the final run. The smooth pursuit paradigm entailed nine runs, and the saccade paradigm entailed eight runs.

In 12 of the 16 subjects who performed in both paradigms, the two paradigms were executed in two sessions on two separate days; in the other four subjects the paradigms were performed in a single session. For these subjects, the chair was rotated to a specific position and a run of the smooth pursuit paradigm was followed by a run of the saccade paradigm.

Analysis

The recorded eye data were parsed for events (blinks, saccades and fixations) and eye positions using the built-in EyeLink software and subsequently analyzed off-line using custom-written software in Matlab (version 2008b).

In the *saccade paradigm*, the primary saccades following a change in target position, either away or toward the center, were marked and extracted for each subject and in each run. For each saccade, the latency (i.e., the time between change in target location and saccade onset), the amplitude and peak velocity were determined. Saccades with a latency smaller than 50 ms, an amplitude below 2° or above 30° of visual angle, with a duration over 150 ms, and/or with a vertical component above 2° of visual angle were discarded. Saccadic amplitude was transformed into a gain value, with the amplitude divided by the size of the target jump.

Saccades were grouped into 12 categories according to six trial types (i.e., the combination of two directions of the saccade (leftward or rightward) and three sizes of the initial target jump away from the center) and two phases within a trial (the unpredictable jump away from the center, evoking a centrifugal saccade, and the predictable change toward the center evoking a centripetal saccade). The median values of the three saccade parameters of interest (latency, gain and peak velocity) were calculated over the ten trials for each of the 12 saccade categories and each of the eight runs separately. The two values of the two runs when the chair was rotated in the neutral position were averaged within each subject. Data were averaged over the direction of chair rotation, since a preliminary analysis showed no effect of the direction of chair rotation.

Statistical analyses were performed by means of repeated measurement ANOVAs, which included four factors ("neck torsion" with four levels: 0, 15, 30 and 45° of chair rotation; "predictability" with two levels: predictable (centripetal) target jumps versus unpredictable (centrifugal) target jumps; "direction" with 2 levels: left or right; and "amplitude" with three levels: 5, 10 or 15° of visual angle). For each of the three outcome parameters of the saccade paradigm (latency, gain and peak velocity), a separate ANOVA was performed.

In the *smooth pursuit paradigm*, 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 s, starting 1 s 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 and a phase lag 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 three sinusoids, with frequencies matching the three target frequencies, was fitted through the eye velocity data. This yielded three 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 gains, phase lags and the number of saccadic intrusions of the second and third measurement, when the chair was rotated in the neutral position, were averaged to obtain values for this chair rotation (the first measurement in this rotation was discarded). For each subject, all 14 gains (obtained for 7 chair rotations and 2 target movement conditions [predictable and unpredictable]) were normalized by dividing them by the median of the 7 gains obtained in the predictable condition. The number of saccadic intrusions were normalized similarly using the median number of saccades for the seven chair rotations in the predictable condition. Data were averaged over the direction of chair rotation, since a preliminary analysis showed no effect of the direction of chair rotation.

Statistical analyses were performed by means of repeated measurements ANOVAs, which included two factors ("neck torsion" with four levels: 0, 15, 30 and 45° of degrees of chair rotation; "predictability" with two levels: predictable versus unpredictable smooth pursuit target motion). For each of the three outcome parameters of the smooth pursuit paradigm (gain, phase difference and number of saccadic intrusions), a separate ANOVA was performed.

All statistical analyses were performed using SPSS (Version 20). Significance level was set at 5 %. In "Results" we will focus on the effects of chair rotation and target predictability (and their interaction with other factors) on the various outcome measures of saccadic and smooth pursuit eye movements.

Results

Saccadic eye movements

The data of 1 subject was discarded, because almost all her predictable centripetal saccades had latencies below 50 ms, leaving 19 subjects to be included in the analysis.

Saccadic gain (Fig. 2a) was not affected by neck torsion and none of the interactions involving neck torsion reached significance. Predictability did affect saccade gain ($F(1,18) = 8.25$, $p = 0.01$, partial $\eta^2 = 0.34$): unpredictable centrifugal saccades had higher gains (0.97 ± 0.02) than predictable centripetal saccades (0.95 ± 0.01). The interaction between predictability and amplitude ($F(2,17) = 27.65$, $p < 0.00$, partial $\eta^2 = 0.77$) showed that the gains of unpredictable centrifugal saccades decreased with amplitude (1.00 ± 0.02, 0.97 ± 0.02 and 0.94 ± 0.01 for 5, 10 and 15° amplitude, respectively; $F(2,17) = 20.56$, $p < 0.00$, partial $\eta^2 = 0.71$), whereas the gains of predictable centripetal saccades did not (0.92 ± 0.02, 0.96 ± 0.01 and 0.96 ± 0.01 for 5, 10 and 15° amplitude, respectively; $F(2,17) = 9.38$, $p = 0.00$, partial $\eta^2 = 0.53$). The interaction between predictability and direction ($F(1,18) = 6.13$, $p = 0.02$, partial $\eta^2 = 0.25$) showed that the difference in gain between leftward saccades and rightward saccades was smaller for predictable centripetal saccades (0.94 ± 0.02 vs. 0.95 ± 0.01) than for unpredictable centrifugal saccades (0.95 ± 0.02 vs. 1.00 ± 0.01, $T(18) = 2.501$, $p = 0.02$) The main effect of direction ($F(1,18) = 7.93$, $p = 0.01$, partial $\eta^2 = 0.31$) showed that rightward saccades had a higher gain (0.97 ± 0.02) than leftward saccades (0.94 ± 0.01). The main effect of amplitude ($F(2,17) = 8.26$, $p = 0.00$, partial $\eta^2 = 0.49$) showed that, overall, saccade gain differed between amplitudes (0.96 ± 0.02, 0.97 ± 0.02 and 0.95 ± 0.01 for 5, 10 and 15° amplitude, respectively).

Saccadic latency (Fig. 2b) was not affected by neck torsion and none of the interactions involving neck torsion reached significance. Predictability did affect latency ($F(1,18) = 82.37$, $p < 0.00$, partial $\eta^2 = 0.82$): unpredictable centrifugal saccades had longer latencies (193 ± 5 ms) than predictable centripetal saccades (166 ± 6 ms). The interaction between predictability and amplitude ($F(2,17) = 12.21$, $p = 0.00$, partial $\eta^2 = 0.59$) showed that latencies of unpredictable centrifugal saccades increased with amplitude (194 ± 5, 192 ± 5 and 214 ± 5 ms for 5, 10 and 15° amplitude, respectively; $F(2,17) = 105.27$, $p < 0.00$, partial $\eta^2 = 0.93$), whereas the latencies of predictable centripetal saccades did not (166 ± 6, 155 ± 5 and 165 ± 5 ms for 5, 10 and 15° amplitude, respectively; $F(2,17) = 44.76$, $p < 0.00$, partial $\eta^2 = 0.84$). There was no interaction between predictability and saccade direction and there was no main effect of direction. The main effect of amplitude showed that, overall, saccade latency differed between amplitudes (180 ± 5, 173 ± 4 and 189 ± 4 ms for 5, 10 and 15° amplitude, respectively; $F(2,17) = 100.66$, $p < 0.00$, partial $\eta^2 = 0.92$).

Saccadic peak velocity (Fig. 2c) was significantly affected by neck torsion ($F(3,16) = 6.39$, $p = 0.01$, partial $\eta^2 = 0.55$). Post hoc analysis using paired *t* tests showed that the peak velocity at neutral position (350 ± 9°/s) was significantly different from the peak velocity at 15° (327 ± 9°/s, $p = 0.00$) and at 30° neck torsion (333 ± 10°/s, $p = 0.01$), but not from the peak velocity at 45° neck torsion (342 ± 9°/s). The peak velocities between 15° and 45° neck torsion differed as well ($p = 0.04$). None of the interactions involving neck torsion reached significance. Predictability did not affect peak velocity. The interaction between predictability and amplitude ($F(2,17) = 51.10$, $p < 0.00$, partial $\eta^2 = 0.86$) was significant. Post hoc comparisons showed that peak velocity increased with amplitude for predictable saccades

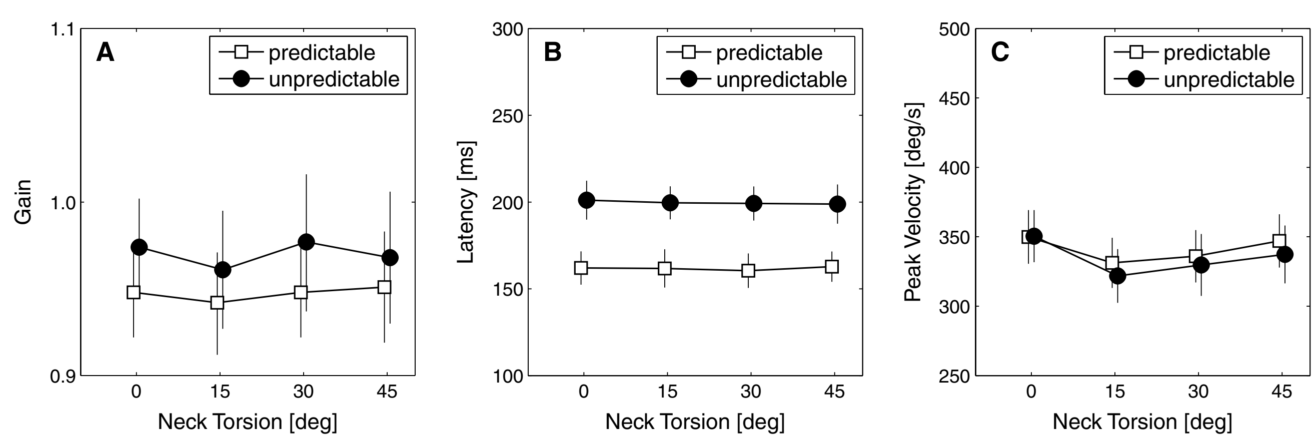

Fig. 2 Saccadic gains (**a**), latencies (**b**) and peak velocities (**c**) for each of the four eccentricities of chair rotation, for predictable centripetal saccades (*closed circles*) and unpredictable centrifugal saccades (*open squares*). *Error bars* represent 95 % confidence interval

(239 ± 6, 351 ± 9 and 425 ± 10°/s for 5, 10 and 15° amplitude, respectively; $F(2,17) = 406.63$, $p < 0.00$, partial $\eta^2 = 0.98$), but less so for unpredictable saccades (253 ± 7, 352 ± 9 and 399 ± 10°/s, for 5, 10 and 15° amplitude, respectively; $F(2,17) = 305.82$, $p < 0.00$ partial $\eta^2 = 0.97$). There was no interaction between predictability and saccade direction. There was no main effect of direction. The main effect of target amplitude showed that, overall, peak velocity differed between amplitudes (246 ± 6°/s, 355 ± 9°/s and 412 ± 10°/s for 5, 10 and 15°, respectively; $F(2,17) = 395.40$, $p < 0.00$, partial $\eta^2 = 0.98$).

In neutral chair rotation, the within-subject correlations between predictable centripetal saccades and unpredictable centrifugal saccades were significant for all parameters measured: saccade gains ($r = 0.78$), latencies ($r = 0.57$) and peak velocities ($r = 0.79$).

We also compared the mean gain, latency and peak velocity between both runs in neutral rotation (i.e., between run 1 and run 8) to assess the possible effects of learning and/or fatigue. No differences in gain or latency were found. Peak velocities of saccades in the first run (350 ± 12°/s) were somewhat higher than the second run in neutral rotation (328 ± 12°/s; $F(1,17) = 7.01$, $p = 0.02$, partial $\eta^2 = 0.29$).

Smooth pursuit eye movements

All 20 subjects were included in the analyses.

Smooth pursuit gain (Fig. 3a) was affected by neck torsion (0.95 ± 0.02, 0.99 ± 0.01, 0.97 ± 0.01 and 0.95 ± 0.01 for 0, 15, 30 and 45° chair rotation, respectively; $F(3,17) = 4.98$, $p = 0.01$, partial $\eta^2 = 0.47$). Predictability did affect smooth pursuit gain ($F(1,19) = 22.74$, $p < 00$, partial $\eta^2 = 0.55$): predictably moving targets yielded higher smooth pursuit gains (1.00 ± 0.00) than unpredictably moving targets (0.94 ± 0.12). The interaction between predictability and neck torsion was not significant.

Phase lags (Fig. 3b) were affected by neck torsion (9.2 ± 0.5, 8.6 ± 0.6, 8.0 ± 0.5 and 9.1 ± 0.6° for 0, 15, 30 and 45° chair rotation, respectively; ($F(3,17) = 3.39$, $p = 0.04$, partial $\eta^2 = 0.37$). Phase lag was higher for unpredictably moving targets (10.3 ± 0.6°) than for predictably moving targets (6.9 ± 0.6°, $F(1,19) = 4.50$, $p = 0.05$, partial $\eta^2 = 0.19$). No interaction between neck torsion and predictability was present.

The normalized number of saccadic intrusions (Fig. 3c) was not affected by neck torsion. Predictability did affect the number of saccadic intrusions ($F(1,19) = 7.22$, $p = 0.02$, partial $\eta^2 = 0.28$): predictably moving targets resulted in more saccades (1.01 ± 0.01) than unpredictably moving targets (0.93 ± 0.03). The interaction between predictability and neck torsion was just not significant ($F(3,17) = 3.04$, $p = 0.06$, partial $\eta^2 = 0.35$). A post hoc analysis suggested that for predictably moving targets, the number of saccadic intrusions increased with increasing neck torsion (93 ± 0.04, 0.96 ± 0.02, 1.03 ± 0.04 and 1.07 ± 0.04 intrusions, for 0, 15, 30 and 45° chair rotation, respectively; $F(3,17) = 3.90$, $p = 0.03$, partial $\eta^2 = 0.41$). For unpredictably moving targets, the number of saccadic intrusions was not affected by neck torsion.

Individual smooth pursuit gains ($r = 0.46$) and number of saccadic intrusions ($r = 0.79$) correlated between predictably moving targets and unpredictably moving targets across 20 subjects in the neutral rotation. Smooth pursuit gains did not correlate with number of saccadic intrusions for predictably ($r = 0.14$) and unpredictably ($r = 0.05$) moving targets.

We compared smooth pursuit gains and numbers of saccades to predictably moving targets between both runs in neutral rotation (i.e., between run 4 and run 9) to assess

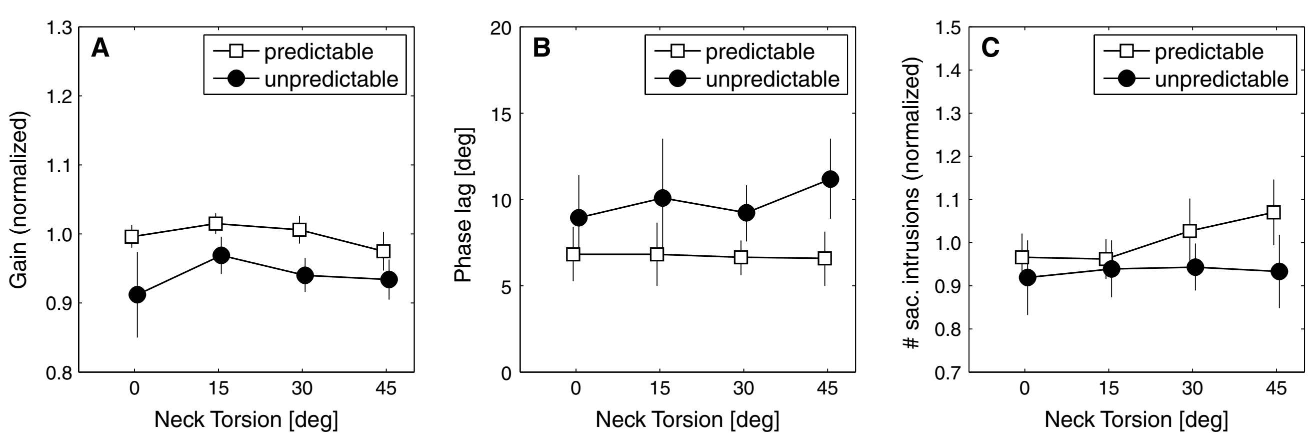

Fig. 3 Normalized smooth pursuit gain (**a**), phase lags (**b**) and normalized number of saccadic intrusions (**c**) for each of the four eccentricities of chair rotation, for predictably moving targets (*closed circles*) and unpredictably moving targets (*open squares*). *Error bars* represent 95 % confidence interval

possible effects of learning and/or fatigue. No significant differences were found in smooth pursuit gains or numbers of saccadic intrusions.

Finally, for the neutral chair rotation, we observed no correlation between the average gain of predictable saccades and the gain of predictable smooth pursuit ($r = 0.32$), or between the average gain of unpredictable saccades and the gain of unpredictable smooth pursuit ($r = 0.19$), using the data of the 16 subjects who participated in both paradigms. Also, we did not see marked differences between the four subjects who performed both paradigms in a single session and the 12 subjects who performed both paradigms in two separate sessions.

Discussion

In this study, we systematically investigated the effect of neck torsion on voluntary eye movements. Using a thorough methodological approach using video-oculography and a range of neck torsions, we found that smooth pursuit as well as saccadic eye movement performance was only mildly affected by static rotation of the trunk relative to the head. The effect was most prominent, but nonetheless small for smooth pursuit eye movements. Using a range of neck torsions from 45° to the left to 45° to the right, a maximum of 5 % change in smooth pursuit gain was observed. Gain was maximal at 15° torsion, but similar gains were observed for neutral (0°) and extreme (45°) neck torsions. For saccadic eye movements, only peak velocity seemed to be influenced by neck torsion, while gain and latency were not. Neutral and extreme neck torsions yielded comparable saccadic peak velocities. These findings of small effects of neck torsion on healthy human voluntary eye movements are in line with previous reports (Prushansky et al. 2004; Treleaven et al. 2005, 2008; Tjell and Rosenhall 1998).

Interestingly enough, optimal performance, as reflected by high gains, was not always encountered at neutral rotations of the trunk, i.e., when the head and trunk were aligned (see Figs. 2a, 3a). Indeed, some subjects spontaneously reported that they found it more convenient to perform the task when they were rotated a little sideways, although this varied between subjects. However, we did not measure this "preferential direction" reliably for proper analysis in the present study. It is recommended that it is taken into account in the design of future studies.

The lack of effect of neck torsion might be explained by an adaptive process. Increased neck torsion could have only transient effects on eye movement control as it is conceivable that the oculomotor system adapts to static changes in afferent cervical input caused by increased neck torsion. This notion could be tested in a setup that allows for applying dynamic chair rotation while presenting visual stimuli (see, e.g., Kelders et al. 2003; Montfoort et al. 2008). In this way, one could disentangle transient from sustained effects of neck torsion on oculomotor control.

In both the saccadic and smooth pursuit paradigm, we manipulated the predictability of the target movements. As expected, unpredictable target jumps yielded higher saccadic latencies. Previous studies suggest that more time is needed in planning a saccade in response to an unpredicted target jump (Gagnon et al. 2002; Wegner and Fahle 1999). An increased latency might also allow for executing a more accurate saccade (McSorley and Findlay 2003). In the present study, gains were higher for increased latencies. The observed interaction between peak velocity and amplitude seems to be in line with previously reported increased peak accelerations for predictably large saccades (Alvarez et al. 2002). An increase in peak velocities could be related to the concurrent increase in gain, given the link between saccade amplitude and velocity which is known as the main sequence (Bahill et al. 1975). Also in the present study, we found this relationship by manipulating the size of the target jump.

In our saccade paradigm, saccades were either predictable or unpredictable with respect to direction and amplitude. However, predictable saccades were always centripetal, whereas unpredictable saccades were always centrifugal. Initial eye position could therefore be a confounding factor (Colllewijn and Erkelens 1988). Eye position, however, does not play a role in saccade generation at a low level. Structures like the superior colliculus and the brainstem encode saccadic direction, amplitude, duration and velocity, independent of initial eye position (Leigh and Zee 2006). Saccadic latencies are more likely to be controlled by cognitive processes that take target predictability into account. These cognitive processes are part of a higher level of oculomotor control in which the frontal eye fields, for instance, play a role (Leigh and Zee 2006). We therefore argue that the differences in saccadic latencies are not caused by different initial eye positions, but rather by target predictabilities.

For smooth pursuit movements, unpredictable target movements impaired smooth pursuit behavior. As expected, adding a frequency component above 0.4 Hz had a decremental effect on smooth pursuit gain of the 0.4 frequency component (Barnes et al. 1987). This effect was found to be present for all neck rotations. However, reduced gains did not lead to an increased number of saccadic intrusions in response to unpredictably moving targets. This could be explained by the notion that it is not useful to make a saccade to a location that is unlikely to be the correct position of the target, since it moves unpredictably. In line with previous research, phase lags increased in the unpredictable condition for which smooth pursuit gain was decreased (Paige 1994).

In the smooth pursuit neck torsion (SPNT) test (Tjell and Rosenhall 1998), smooth pursuit is measured in response to predictable target motion. Importantly, smooth pursuit performance is compared between neutral position and a position with (extreme) neck torsion, which circumvents issues related to between-subject differences that are, for instance, related to variations in cognitive abilities. We observed that the effect of neck torsion was not affected by target predictability. This suggests that one does not need to use unpredictable targets to compare groups of subjects, for instance, patients with neck pain and healthy controls. Even so, it might be worthwhile to use both predictable and unpredictable target motions to investigate how cognitive factors affect oculomotor behavior in patients with neck pain. For instance, patients with cognitive impairments due to frontal lobe degeneration show deficits in predicting target movements during smooth pursuit (Coppe et al. 2012). It has been reported that patients with neck pain due to WAD also show more self-reports of cognitive complaints (Sullivan et al. 2002). It could be that these patients are less able to predict target motion and therefore show impairments in smooth pursuit performance. Although speculative, this impairment could be more pronounced in more challenging circumstances, i.e., when the neck of the patient is in extreme torsion. However, both the effect of target predictability itself and its potential interaction with neck torsion have not been investigated in patients with neck pain.

The present study has several limitations. For instance, our subjects were rather young and it is known that eye movement performance changes with age (Munoz et al. 1998). Therefore, one cannot extrapolate the current findings to the general population. Furthermore, we only tested eye movements and neck torsion in the horizontal plane. Given the distinct neuronal pathways for horizontal and vertical eye movements (Leigh and Zee 2006), it might be that neck torsion in different planes (tilt and roll) might yield different results.

In conclusion, applying static neck torsion to healthy human subjects resulted in minimal changes in oculomotor control, not only for smooth pursuit eye movements, but also for saccadic eye movements. These effects were not modulated by target predictability, which, in itself, had clear effects on saccadic and smooth pursuit performance.

Our findings are in line with previous observations about the effect of neck torsion on smooth pursuit eye movements in healthy individuals. As in the SPNT test, we did not find significant differences between no neck torsion (neutral rotation, 0°) and extreme neck torsion (45° rotation). Therefore, the methodological issues mentioned in the introduction do not seem to reduce the clinical relevance of the SPNT test to assess the cervical afferent influence on smooth pursuit eye movements. However, the use of video-oculography allows for a more detailed analysis of smooth pursuit behavior including saccadic intrusions and phases. Using more chair rotations provides a more complete view of the effect of neck torsion, for instance, by taking an individual torsion preference into account. Finally, using both predictable and unpredictable targets could give more insight into the interaction between (impaired) cognitive processes and smooth pursuit. Therefore, when given the opportunity, we recommend that future studies, for instance on the oculomotor control of patients with neck pain, include both predictably and unpredictably moving targets and use a range of neck torsions. This could be a useful and informative supplement of the SPNT test, although we realize that this might be difficult in clinical practice. Further studies are warranted to investigate how the head and eye movement systems interact to produce efficient gaze shifts in humans.

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