ORIGINAL ARTICLE

Vestibulo-ocular reflex and motion sickness in figure skaters

**Sébastien Tanguy · Gaëlle Quarck · Olivier Etard ·
Antoine Gauthier · Pierre Denise**

Abstract   In order to determine the effect of figure skating
on the functional plasticity of the vestibular system, we
quantified vestibulo-ocular reflex (VOR) and motion sick-
ness (MS) intensity in 11 female figure skaters and 11
matched control subjects. Vestibular stimulation consisted
of three cycles of sinusoidal rotation (0.025 Hz, $\pm 60°/s$)
and two velocity steps of 60°/s (acceleration $60°/s^2$). Nau-
seogenic stimulation consisted of a constant velocity (60°/s)
off vertical axis rotation (OVAR) using a 15° tilt angle.
Subjective sickness symptoms were rated immediately after
OVAR with the Pensacola diagnostic index. During sinu-
soidal stimulations, the skaters' VOR, as compared with
that of the controls, demonstrates a gain that is 27% lower
(0.44 ± 0.12 vs. 0.58 ± 0.10; $P < 0.01$) and a phase
advance ($10 \pm 12°$ vs. $-0.3 \pm 6.4°$; $P < 0.05$). During
velocity steps, the VOR gain is 32% lower among the skat-
ers (0.52 ± 0.14 vs. 0.71 ± 0.12; $P < 0.01$), but there is no
difference in time constant (10.8 ± 1.8 s vs. 10.5 ± 2.7 s;
$P = 0.78$). Nauseogenic stimulation evokes significantly
less MS in figure skaters than in control subjects (2.8 ± 2.8
vs. 16.2 ± 13.7; $P < 0.01$). Quantitative alterations in VOR
parameters observed in figure skaters probably result from
vestibular habituation induced by repeated unusual stimula-
tions when practicing figure skating.

Keywords   Figure skating · Vestibulo-ocular reflex ·
Habituation · Adaptation · Motion sickness

S. Tanguy · G. Quarck (✉) · O. Etard · A. Gauthier · P. Denise
UPRES-EA 3917 Mobilités: Cognition et Temporalité,
Faculté de médecine, Université de Caen Basse-Normandie,
14032 Caen Cedex, France
e-mail: gaelle.quarck@wanadoo.fr

Introduction

The vestibular system is continuously involved in equili-
bration reactions. It transmits information that triggers the
vestibulo-ocular reflexes (VOR). The VOR consists of
compensatory eye movements in the opposite direction of
head movement, enabling stabilization of the gaze with
respect to one's surroundings. This transmitted information
also initiates vestibulo-spinal reflexes providing stabiliza-
tion of the body. Acrobatic sports such as figure skating
strongly stimulate the vestibular system. The performance
of the vestibular system is generally assessed by means of
VOR as it is relatively easy to quantify accurately. Thus,
during rotation in the dark around a vertical axis, the sud-
den start of the rotary chair (velocity-step, VS) induces an
ocular nystagmus characterized by slow compensatory
phases (in the opposite direction of rotation) alternating
with fast phases (Fig. 3). The velocity of the slow phases
very quickly reaches a peak then decreases exponentially
down to zero. When rotation stops, we observe an eye
response in the opposite direction (post-rotational nystag-
mus). The VOR can be modelled as a first order high-pass
linear filter entirely defined by two parameters: gain, the
ratio between maximum slow phase eye velocity and head
angular velocity, and the time constant of the exponential
decrease (TC) (Robinson 1981). Results from experiments
on Monkeys, Cats and Humans (Blair and Gavin 1979;
Clement et al. 2002; Jäger and Henn 1981) show that
repeated vestibular stimulations induce a decrease in the
gain and a shortening of the TC, a phenomenon known as
habituation. An increase in phase advance is also reported
during stimulations at sinusoidal velocity (Fig. 2) which is
theoretically equivalent to a decrease in the TC (Robinson
1981). This decrease in TC during habituation does not result
from peripheral alterations but probably from adaptation in

the velocity storage mechanism (Cohen et al. 1992; Green and Angelaki 2004). A number of studies have been devoted, with sometimes conflicting results, to highlighting vestibular habituation in populations engaged in activities that produce powerful stimulation of the vestibular apparatus. In ballet dancers, the vestibular response appears shorter (Tschiassny 1957) and the nystagmus slow phase velocity is lower (Osterhammel et al. 1968). The VOR of gymnasts is characterized by a 15% shortening of TC and by a 25% decrease gain with an asymmetry producing a more marked decrease in counterclockwise rotation (Quarck and Denise 2005). Among fighter pilots, the duration of the post-rotational nystagmus is shorter (Aschan 1954), but two studies have observed an increased gain, which seems out of step with the rest of the literature (Lee et al. 2004; Schwarz and Henn 1989).

The literature dealing with VOR characteristics of figure skating includes only two studies with contradictory results: the first one observed only two skaters and revealed strong habituation (McCabe 1960) whereas the second failed to find any modification to VOR but it had no control group (Collins 1966). This particular sport is different from others in that, under international federation rules, skaters are always required to turn in the same direction in performing their rotations. If the vestibular system is stimulated unidirectionally, we may expect to see, as in animals (Clement et al. 1981; Usami et al. 1988), unidirectional habituation with clockwise–counterclockwise VOR asymmetries, as has already been demonstrated in gymnasts (Quarck and Denise 2005).

Vestibular habituation seems to be accompanied by reduced motion sickness (MS). Thus, after a month of regular navigation, candidates for future maritime service become less sensitive to seasickness and show VOR habituation (Shupak et al. 1990). Likewise, repeated stimulation of the vestibular system as part of cosmonaut vestibular training induced both a reduction in gain and TC and a parallel decrease in MS (Clement et al. 2001). Repetitive vestibular stimulation can therefore cause changes in VOR and at the same time a reduction in sensitivity to MS. These parallel alterations in VOR and MS susceptibility probably results from modifications in spatial-temporal properties of the velocity storage mechanism (Bos and Bles 2002; Bos et al. 2002; Dai et al. 2003; DiZio and Lackner 1991; Quarck et al. 1998).

The aim of this study is to evaluate the effect of figure skating on the functional plasticity of the vestibular system by comparing VOR characteristics and MS susceptibility in figure skaters to those of control subjects. More specifically, we formulate the following hypotheses: in comparison with a control group, the skaters present (1) habituation of their VOR, with a lower gain, a shorter time constant and an increased VOR phase advance; (2) VOR asymmetry with habituation in the preferred direction of rotation; (3) greater resistance to MS induced by a nauseogenic rotational test.

Methods

Subjects

We selected 11 female figure skaters (age 13.8 ± 2.5 years; min = 11 years; max = 18 years) practicing approximately 10 hours per week and doing counterclockwise rotations, and 11 sex and age-matched control subjects (age 13.7 ± 2.9 years; min = 9 years; max = 19 years) engaging in some physical activity without high vestibular activation involvment. The subjects chosen were young because people over the age of 18 seldom engage in figure skating. Subjects with past or present otologic or neurological disorders were not included in the study. The study was approved by the ethical committee (CCPPRB) of Lower-Normandy. All subjects, as well as their parents for subjects under 18, gave written informed consent before participating in this study.

Vestibular stimulation and motion sickness evaluation

The subject was seated in a rotary chair, then immobilized using a harness, with the head held in place using a bite-bar. Each subject underwent three sequences of stimulation during a single experimental session. All the tests were carried out in complete darkness. In the first sequence, the chair did a sinusoidal rotation around a vertical axis for 120 s (0.025 Hz, amplitude $\pm 60°/s$). The two following sequences were identical, except the direction of rotation, which was inverted from one sequence to the next (randomized order) (Quarck et al. 2000). For each direction of rotation, the test involved three stages (see Fig. 1). (1) An Earth vertical axis rotation (EVAR), the velocity step rising from 0 to 60°/s in 1 s during a 90 s period (per-rotatory stimulation). (2) An off vertical axis rotation (OVAR) immediately after the first EVAR with a tilt angle of 15° and a rotational velocity of 60°/s chosen to make the examination moderately nauseogenic (Denise et al. 1996b). After 120 s of OVAR, the axis was repositioned vertically and rotation continued at constant velocity for 60 s. (3) A second EVAR: the rotation was stopped in 1 s causing a post-rotatory stimulation in the other direction for 90 s. The sinusoidal test and the velocity step (per and post-rotatory) stimulate the semi-circular canals. OVAR produce otolith stimulation. MS symptoms were assessed after each experimental session with the Pensacola diagnostic index methodology that yields a score between 0 (no symptoms) and 61 (maximum symptoms) (Graybiel et al. 1968).

Fig. 1 Earth vertical axis rotation (EVAR) and off vertical axis rotation (OVAR) graphical representation of the order of stages
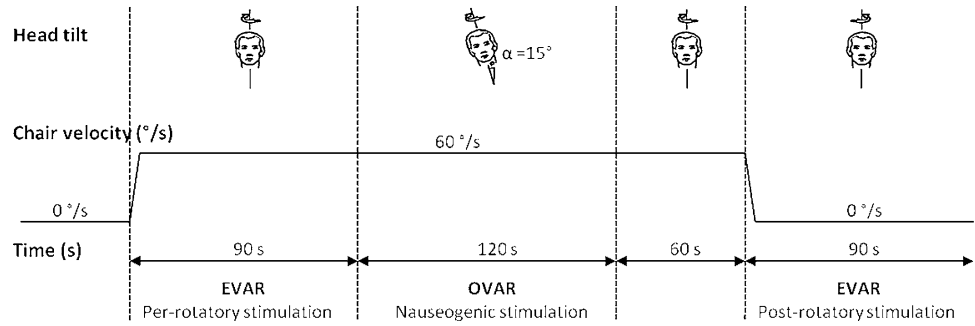
Oculomotor measures

Eye movements were recorded by video-oculography (Chronos Eye Tracker, Chronos Vision, Berlin). Each experimental session started and finished with a calibration accomplished using sequentially illuminating light emitting diodes (0°, ±5°, ±10°, ±15 and ±20°). The chair and eye positions were sampled at 100 Hz. Eye movement velocity was calculated digitally using the two-point central difference algorithm with step size of 50 ms (Bahill and McDonald 1983). From the eye velocity signal, the saccadic eye

movements were removed and replaced by a linear interpolation resulting in a slow phase velocity (SPV) (Denise et al. 1996a), then systematically checked and corrected manually as required. All subsequent analyses were performed on SPV (Figs. 2, 3).

For sinusoidal rotation, a sinusoid of the same period as the stimulation was adjusted onto the SPV. The gain was then calculated as being the ratio of the amplitude of the adjusted sinusoid to stimulation velocity amplitude; the VOR phase shift (°) was defined in relation to the stimulation. For the pre- and post-rotatory stimulations, an
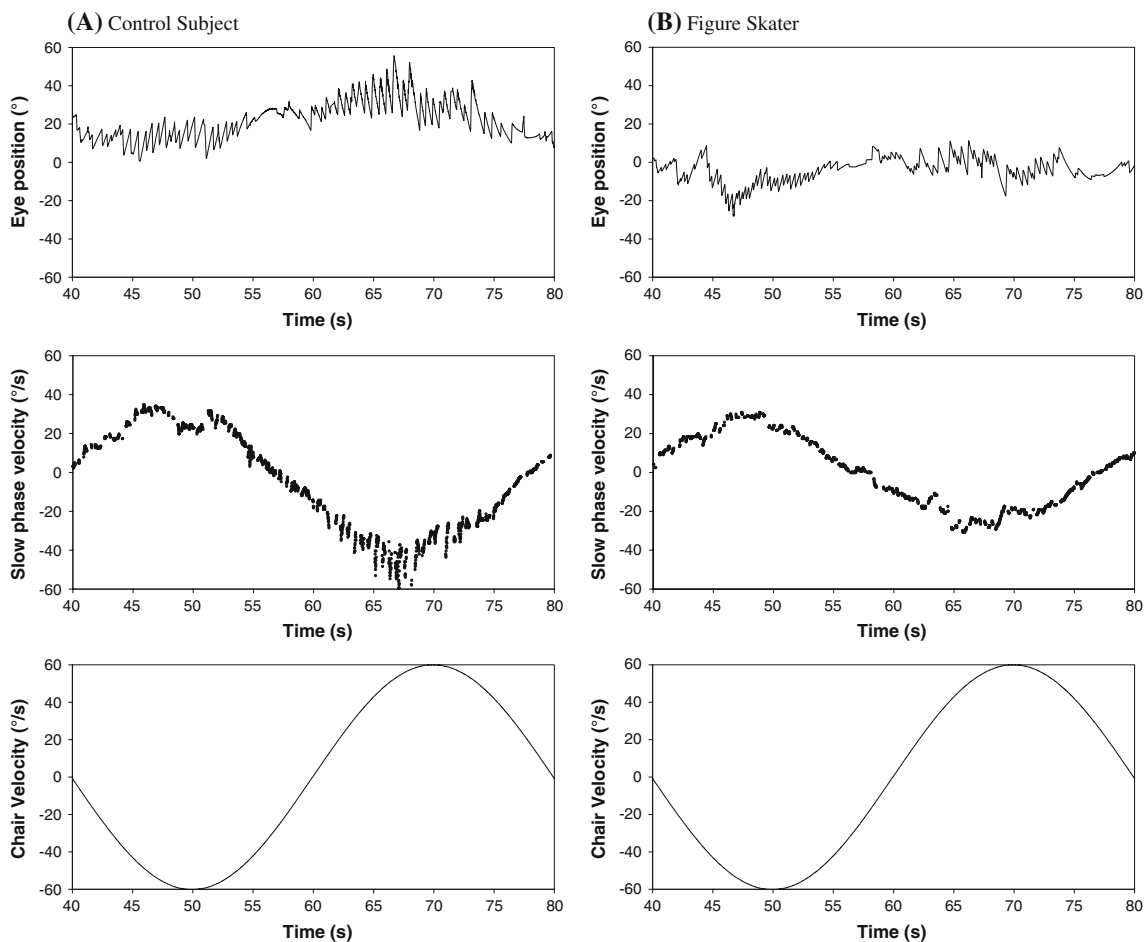

Fig. 2 Typical eye position and slow phase velocity pattern of a control subject
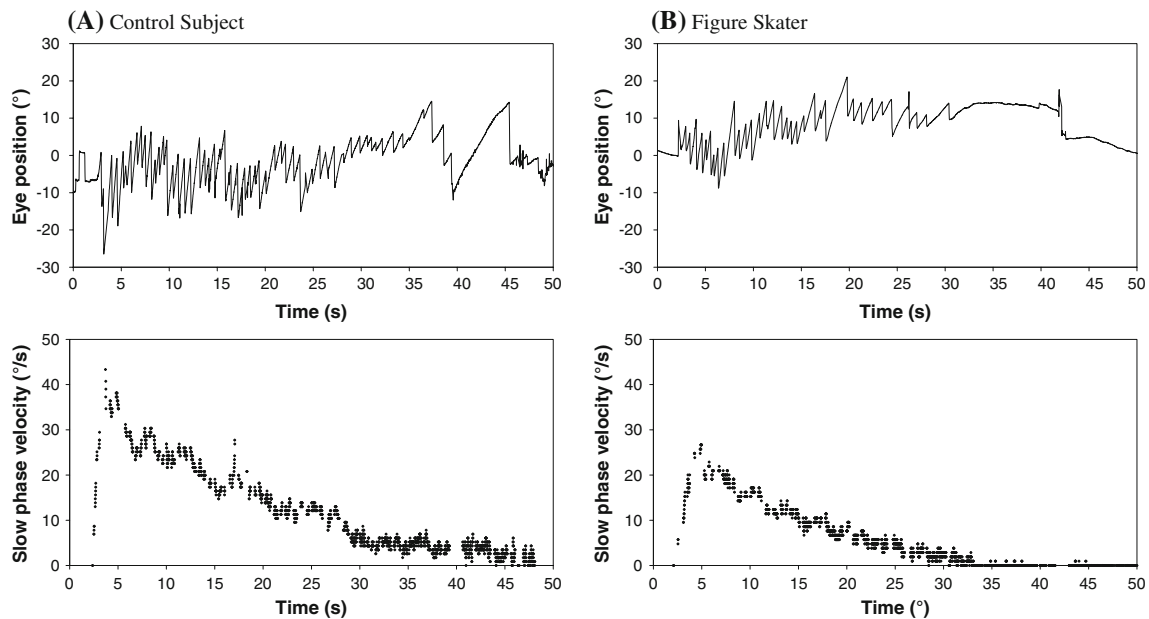
Fig. 3 Typical eye position and slow phase velocity pattern of a control subject

exponential curve was fit on the SPV. The variables studied were the peak slow phase velocity (V_i) and TC (s) of the exponential decrease of SPV. The TC was estimated as the time at which the area subtended by the SPV curve is equal to 63% ($1 - 1/e$) of the total area subtended by entire SPV curve (Denise et al. 1996a). The peak slow phase velocity (V_i) was the fastest slow phase, which was determined manually. The mean value of the TC and the gain (measured as the ratio between V_i and constant head rotation velocity) were calculated from the values obtained during the four examinations: clockwise (CW) per and post-rotatory and counterclockwise (CCW) pre and post-rotatory. The CW and CCW data were pooled because there were no significant differences between the four examinations. The gain and TC CW–CCW asymmetries were calculated using the following formulae: (gain$_{cw}$ – gain$_{ccw}$)/(gain$_{cw}$ + gain$_{ccw}$); (TC$_{cw}$ – TC$_{ccw}$)/(TC$_{cw}$ + TC$_{ccw}$).

Statistical analysis

The data are presented as means and standard deviations. The control and skater groups were compared using the non paired Student t test. To compare certain variables, the Student unequal variance t test was used, in which case the *P* of homogeneity of variances is given. The threshold of statistical significance was set to 0.05.

Results

During sinusoidal stimulation, the VOR gain is significantly lower (27%) for the skater group than for the control

group (0.44 ± 0.12 vs. 0.58 ± 0.10; $P < 0.01$) (Fig. 4). The skaters' responses are 10° phase advance compared with the control group's responses ($10 \pm 12°$ vs. $-0.3 \pm 6.4°$; $P < 0.05$, $P_{variances} < 0.05$) (Fig. 3).

During a velocity step, the VOR gain is significantly lower (32%) for the skater group compared to the control group (0.52 ± 0.14 vs. 0.71 ± 0.12; $P < 0.01$) (Fig. 5). There is no significant difference in the TC between the two groups (10.8 ± 1.8 s vs. 10.5 ± 2.7 s; $P = 0.78$) (Fig. 5).

The VOR gain asymmetry and TC asymmetry in the two groups do not differ significantly. The gain asymmetry in skaters versus control was 0.05 ± 0.15 and -0.02 ± 0.07, $P = 0.15$, $P_{variances} < 0.05$, respectively. The TC asymmetry was -0.01 ± 0.18 and -0.04 ± 0.09, $P = 0.57$, $P_{variances} < 0.05$, respectively.

After the vestibular stimulation session on the rotary chair, the MS score is significantly lower in the skater group compared to the control group (2.8 ± 2.8 vs. 16.2 ± 13.7; $P < 0.01$, $P_{variances} < 0.00001$) (Fig. 6).

Discussion

In both experimental conditions used in this study, i.e. sinusoidal rotation and velocity step, we observed a decrease in VOR gain of 27 and 32%, respectively, among the skaters. Moreover, during sinusoidal stimulation, we saw a 10° phase advance in the skaters. Experimental works on VOR habituation in animals also showed a decrease in gain and a increased phase advance (Baloh et al. 1982; Blair and Gavin 1979; Clement et al. 2002; Jäger and Henn 1981). Similar results were observed in umans performing ballet

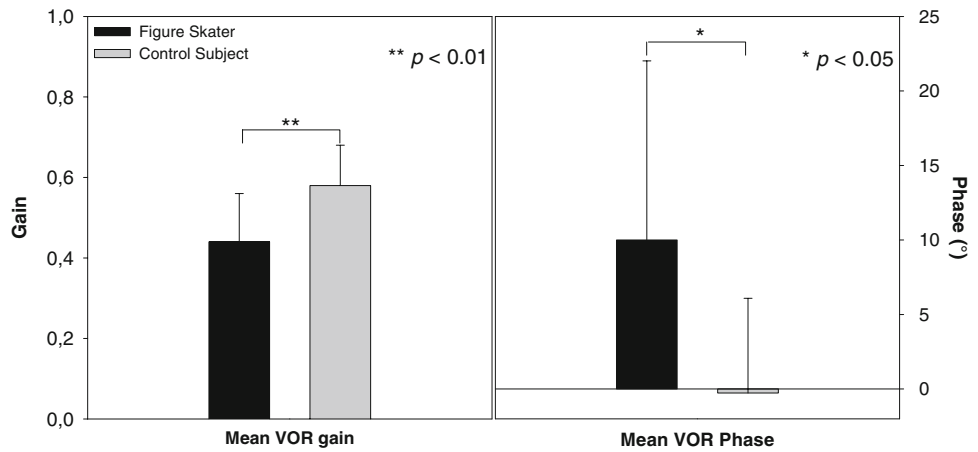**Fig. 4** Vestibulo-ocular reflex (VOR) gain and phase during sinusoidal EVAR

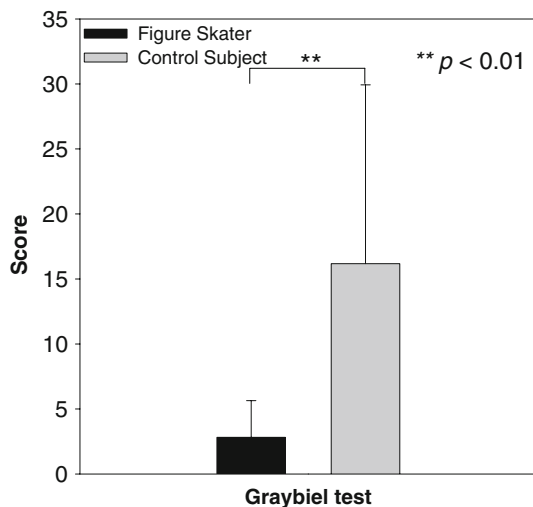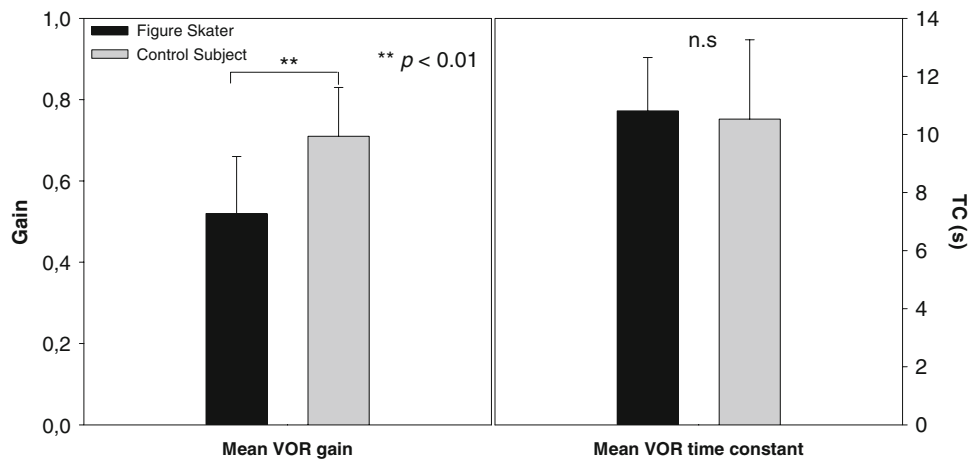**Fig. 5** Vestibulo-ocular reflex gain and time constant during velocity-step EVAR

Fig. 6 Motion sickness score after OVAR

decrease during velocity step stimulation appears to contradict the phase advance: in a simplified high-pass first-order model of the VOR, reduction of gain and phase advance at low frequencies of sinusoidal rotation is equivalent to an isolated decrease of the TC (Robinson 1981).Thus, this model seems appropriate to describe the habituation in animals and human adults, but probably not in children with a vestibular system in the process of maturation and we have no model available for the young subject (0–18 years). Indeed, owing to their youth, VOR maturation in most of our subjects was in complete (Yagi et al. 1983) while mature and immature vestibular systems are probably affected differently by vestibular habituation. Thus, the relationship between phase (sinusoidal stimulation) and TC (step stimulation) could be different in young versus adult subjects.

In animals, repetitive unidirectional rotations induce unidirectional habituation (Clement et al. 1981; Usami et al. 1988). As far as we know, only one study has highlighted this phenomenon in humans: gymnasts show unidirectional habituation in their preferred direction of rotation (Quarck and Denise 2005). Although all the skaters in our study always did their rotations in the same direction; CCW. Our results show no significant difference between the

(Osterhammel et al. 1968; Tschiassny 1957) and gymnastics (Quarck and Denise 2005). The VOR modifications observed in the skaters are thus in agreement with experimental works on habituation of the vestibular system in humans and animals. Conversely, the absence of any TC

responses seen in the CW versus the CCW rotation. There again, the discrepancy with the study by Quarck and Denise (2005) may be explained in terms of subjects' age: adults in the Quarck et al. study and young people in ours. It may be that vestibular system maturation is masking TC habituation and VOR asymmetry phenomena in these still developing subjects. Another explanation might be linked to the characteristics of vestibular stimulation. We envisaged the hypothesis of unidirectional habituation by considering that the angular accelerations sustained by skaters are asymmetrical. However there remains the possibility that the acceleration levels at the start and end of the figure are not very different and therefore induce symmetrical habituation even with unidirectional rotations. To verify this hypothesis an accurate measurement of the acceleration in the skaters' heads while executing figures would be required.

In addition to changes in VOR gain and phase, we observed a distinct decrease in the MS provoked by OVAR in the skaters. This is the first time a reduced sensitivity to MS has been highlighted in people engaging in this type of sporting activity. This result is consistent with the increase in resistance to MS observed after vestibular habituation induced either by cosmonaut vestibular training (Clement et al. 2001) or by a month spent at sea (Shupak et al. 1990). Even if the VOR tends to decrease through a habituation phenomenon, the skaters use vestibular information more efficiently for postural control. Indeed, they are subject neither to dizziness nor to MS nor even to disorientation following multiple rotations on the ice the way untrained people might be.

In summary, skaters, even at a very young age, show signs of vestibular habituation and reduced sensitivity to MS. In this study, only the canal-ocular reflex was studied, although the otolith-ocular reflex may also be under the control of adaptive process (Koizuka 2003). The otolith-ocular reflex is that which arises from the otolith organs, the parts of the inner ear that sense gravity and linear acceleration. In a parallel study performed on the same type of population we also found significant modifications of otolith-ocular reflex (Tanguy et al. 2008). The combined results of these two studies suggest that both canal and otolith components of the vestibular reflexes are heavily modified by the practice of skating.

Furthermore, a study of a population of adult figure skaters would be desirable in order to dissociate maturation phenomena from VOR habituation phenomena.

References

Aschan G (1954) Response to rotatory stimuli in fighter pilots. Acta Otolaryngol 116:24–31. doi:10.3109/00016485409130269

Bahill AT, McDonald JD (1983) Frequency limitations and optimal step size for the two-point central difference derivative algorithm with applications to human eye movement data. IEEE Trans Biomed Eng 30:191–194. doi:10.1109/TBME.1983.325108

Baloh RW, Henn V, Jäger J (1982) Habituation of the human vestibulo-ocular reflex with low-frequency harmonic acceleration. Am J Otolaryngol 3:235–241. doi:10.1016/S0196-0709(82)80061-6

Blair S, Gavin M (1979) Response of the vestibulo-ocular reflex to differing programs of acceleration. Invest Ophtalmol Vis Sci pp 1086–1090

Bos JE, Bles W (2002) Theoretical considerations on canal-otolith interaction and an observer model. Biol Cybern 86:191–207. doi:10.1007/s00422-001-0289-7

Bos JE, Bles W, de Graaf B (2002) Eye movements to yaw, pitch, and roll about vertical and horizontal axes: adaptation and motion sickness. Aviat Space Environ Med 73:436–444

Clement G, Courjon JH, Jeannerod M, Schmid R (1981) Unidirectional habituation of vestibulo-ocular responses by repeated rotational or optokinetic stimulations in the cat. Exp Brain Res 42:34–42. doi:10.1007/BF00235726

Clement G, Deguine O, Parant M, Costes-Salon MC, Vasseur-Clausen P, Pavy-LeTraon A (2001) Effects of cosmonaut vestibular training on vestibular function prior to spaceflight. Eur J Appl Physiol 85:539–545. doi:10.1007/s004210100494

Clement G, Flandrin JM, Courjon JH (2002) Comparison between habituation of the cat vestibulo-ocular reflex by velocity steps and sinusoidal vestibular stimulation in the dark. Exp Brain Res 142:259–267. doi:10.1007/s00221-001-0930-7

Cohen H, Cohen B, Raphan T, Waespe W (1992) Habituation and adaptation of the vestibuloocular reflex: a model of differential control by the vestibulocerebellum. Exp Brain Res 90:526–538. doi:10.1007/BF00230935

Collins W (1966) Vestibular responses from figure skaters. Aerosp Med 37:1098–1104

Dai M, Kunin M, Raphan T, Cohen B (2003) The relation of motion sickness to the spatial–temporal properties of velocity storage. Exp Brain Res 151:173–189. doi:10.1007/s00221-003-1479-4

Denise P, Darlot C, Ignatiew-Charles P, Toupet M (1996a) Unilateral peripheral semicircular canal lesion and off-vertical axis rotation. Acta Otolaryngol 116:361–367. doi:10.3109/00016489609137858

Denise P, Etard O, Zupan L, Darlot C (1996b) Motion sickness during off-vertical axis rotation: prediction by a model of sensory interactions and correlation with other forms of motion sickness. Neurosci Lett 203:183–186. doi:10.1016/0304-3940(96)12303-X

DiZio P, Lackner JR (1991) Motion sickness susceptibility in parabolic flight and velocity storage activity. Aviat Space Environ Med 62:300–307

Graybiel A, Wood CD, Miller EF, Cramer DB (1968) Diagnostic criteria for grading the severity of acute motion sickness. Aerosp Med 39:453–455

Green AM, Angelaki DE (2004) An integrative neural network for detecting inertial motion and head orientation. J Neurophysiol 92:905–925. doi:10.1152/jn.01234.2003

Jäger J, Henn V (1981) Habituation of the vestibulo-ocular reflex (VOR) in monkey during sinusoidal rotation in the dark. Exp Brain Res 41:108–114. doi:10.1007/BF00236599

Koizuka I (2003) Adaptive plasticity in the otolith-ocular reflex. Auris Nasus Larynx 30(Suppl):S3–S6. doi:10.1016/S0385-8146(02)00117-7

Lee MY, Kim MS, Park BR (2004) Adaptation of the horizontal vestibuloocular reflex in pilots. Laryngoscope 114:897–902. doi:10.1097/00005537-200405000-00021

McCabe BF (1960) Vestibular suppression in figure skaters. Trans am acad ophthalmol otolaryngol 64:264–268

Osterhammel P, Terkildsen K, Zirstorff K (1968) Vestibular habituation in ballet dancers. Acta Otolaryngol 66:221–228. doi:10.3109/00016486809126289

Quarck G, Denise P (2005) Caractéristiques du réflexe vestibulo-oculaire chez les gymnastes. Science et Motricité

Quarck G, Etard O, Darlot C, Denise P (1998) Motion sickness susceptibility correlates with otolith- and canal-ocular reflexes. Neuroreport 9:2253–2256. doi:10.1097/00001756-199807130-00019

Quarck G, Etard O, Oreel M, Denise P (2000) Motion sickness occurrence does not correlate with nystagmus characteristics. Neurosci Lett 287:49–52. doi:10.1016/S0304-3940(00)01140-X

Robinson DA (1981) The use of control systems analysis in the neurophysiology of eye movements. Annu Rev Neurosci 4:463–503. doi:10.1146/annurev.ne.04.030181.002335

Schwarz U, Henn V (1989) Vestibular habituation in student pilots. Aviat Space Environ Med 60:755–761

Shupak A, Kerem D, Gordon C, Spitzer O, Mendelowitz N, Melamed Y (1990) Vestibulo-ocular reflex as a parameter of seasickness susceptibility. Ann Otol Rhinol Laryngol 99:131–136

Tanguy SG, Quarck GM, Etard OM, Gauthier AF, Denise P (2008) Are otolithic inputs interpreted better in figure skaters? Neuroreport 19:565–568

Tschiassny K (1957) Studies concerning vestibular factors in the ballet dancer, the pigeon and the blind person. Trans Am Acad Ophtalmol Otolaryngol pp 503–506

Usami S-I, Igarashi M, Ishii M, Hozawa J (1988) Unidirectional vestibular habituation in the squirrel monkey. The time course and its influence on optokinetic nystagmus. Acta Otolaryngol Suppl 106:124–129. doi:10.3109/00016488809107379

Yagi T, Sekine S, Shimizu M (1983) Age-dependent changes in the gains of the vestibulo-ocular reflex in humans. Adv Otorhinolaryngol 30:9–12