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RESEARCH ARTICLE

The "ways" we look at dreams: evidence from unilateral spatial neglect (with an evolutionary account of dream bizarreness)

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Abstract Despite decades of research, the question of whether the rapid eye movements (REMs) of paradoxical sleep (PS) are equivalent to waking saccades and whether their direction is congruent with visual spatial events in the dream scene is still very controversial. We gained an insight into these questions through the study of a right brain damaged patient suffering attentional neglect for the left side of space and drop of the optokinetic nystagmus (OKN) with alternating rightward slow/leftward fast phases evoked by rightward optic flow. During PS the patient had frequent Nystagmoid REMs with alternating leftward slow/rightward fast phases and reported dreams with visual events evoking corresponding OKN such as a train running leftward. By contrast, just as in waking OKN, Nystagmoid REMs with alternating rightward slow/leftward fast phases were virtually absent. REMs followed by staring eye position or by consecutive REMs were also observed: these showed no asymmetry comparable to that of Nystagmoid ones. The selective disappearance of Nystagmoid REMs in one horizontal direction proves, for the first time, that in humans different types of REMs exists and that these are driven by different premotor mechanisms. Concomitant drop of OKN and Nystagmoid REMs toward the same horizontal direction demonstrates that phylogenetically ancient oculomotor mechanisms, such as the OKN, are shared by waking and PS. On this evidence and converging findings from animal, neuropsychological and brain imaging studies, a new evolutionary account of dream bizarreness is proposed. Classification and labelling of the different types of REMs are also provided.

Keywords Spatial neglect · Dreaming · REM sleep · Saccade · Nystagmus · Optokinetic

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Introduction

During phases of paradoxical sleep (PS) characterised by isolation of the central nervous system from afferent sensory input, skeletal muscle atonia with blockade of motor output, desynchronised cortical activity and dreaming, the brain produces rapid eye movements (REMs; Pace-Schott and Hobson 2002). It is much debated whether REMs are similar to waking rapid eye movements and whether there is a relationship between their direction and the spatial events in the dream scene (Dement and Kleitman 1957; Hobson and McCarley 1977; Herman et al. 1984). For instance, it is often assumed that REMs are triggered by PS-dependent cholinergic mechanisms in the mesopontine junction (Pace-Schott and Hobson 2002; Vertes 1984) and that, as such, they have no counterpart in waking rapid eye movements as saccades or quick phases of nystag-

mus, either in physiological or psychophysical terms (i.e. velocity and amplitude/velocity relationship; Aserinsky et al. 1985; Vanni-Mercier et al. 1994). This position, however, is not unanimous since evidence from animal and human research suggests neurophysiological and psychophysical similarities between REMs and saccades performed in darkness (Jeannerod and Mouret 1962; Herman et al. 1983) or associated with the startle orienting response (Bowker and Morrison 1976). Furthermore, as with waking saccades, complex interplay in the generation of REMs between oculomotor structures in the brainstem, midbrain and the cortex is suggested by the loss of REMs directed leftward in patients with left unilateral attentional neglect due to right brain damage well outside the brainstem (Doricchi et al. 1993, 1996).

A second important issue related to the study of REMs is their relationship with the visual content of the dream. In their original "scanning hypothesis", Dement and Kleitman (1957) proposed inherent correspondence between the direction of REMs and gazing of the dreamer at the dream scene. A number of studies confirmed this hypothesis (Herman et al. 1984; Dement 1964; Hong et al. 1997) while others suggested that only isolated REMs, as opposed to those appearing in bursts, have a directional relationship with the spatial organisation of the dream scene, thus refuting the idea that all REMs are dream related (Jacobs et al. 1972; Soh et al. 1992).

We shed new light on both questions in a study of a 68-year-old right-handed man, BQ, who had suffered moderate left unilateral neglect (i.e. defective attention and orienting toward the left side of space; Doricchi and Tomaiuolo 2003; Thiebaut de Schotten et al. 2005) subsequent to right hemisphere stroke in the territory of the middle cerebral artery (Fig. 1).

Materials and methods

Case study

Five weeks after the stroke, BQ had severe contralesional hemiplegia. Dynamic ophthalmologic visual field testing revealed a restriction in the left lower quadrant of the right eye sparing the central 10° of the visual field. Moderate left attentional neglect was found when the patient was asked to cancel out targets positioned on the left and right side of an horizontally oriented A4 paper sheet: (a) letter cancellation: 6 targets cancelled over 53 on the left side, right side 40/51; (b) line cancellation: left side 10/11, right side 10/10. No marked neglect was present in the bisection of horizontal lines (five trials, line length = 200 mm, rightward deviation = 3.7 mm). The patient showed no neglect for the left side of his own body (i.e. personal neglect) and no anosognosia of his motor impairments. Importantly he had no topographical neglect when describing three famous squares from his hometown, Rome, from memory (Bisiach and Luzzatti 1978). The only other relevant deficit was mild constructional apraxia in copy drawing. BQ had good performance on short term verbal memory (digit span, i.e. repetition of series of random numbers: raw score = 6/9, score normalised for age and educational level = 4, range 0–4) and medium performance on short term spatial memory (Corsi span, i.e. reproduction of series of spatial positions presented in the attended right hemispace: raw score = 4/9, normalised score = 2, range 0–4).

Study of waking eye movements

Horizontal and vertical eye movements were recorded with DC bipolar electroculographic derivations (EOG) with Ag–AgCl electrodes placed at the outer canthi and above and below the right eye. EOG calibration was performed by asking the patient to fixate dimly lighted LEDs positioned 20° and 10° to the right, to the left and above or below a central LED aligned to the eyes and to the head–body midsagittal plane. EOG signals were amplified, filtered, digitalized (sampling rate 200 Hz) and stored on a PC for off-line processing with specially designed Matlab software (Doricchi et al. 2002).

Clinical examination with EOG recording showed that the patient was able to perform leftward and rightward saccades and had no sign of spontaneous nystagmus. We measured the frequency, amplitude and velocity of the leftward and rightward slow and fast phases of: (a) the vestibular ocular response (VOR) evoked by turns around the vertical head–body axis in complete darkness; (b) the vestibular–optokinetic response (VOR–OKN) evoked by turns inside a lighted optokinetic drum; (c) the optokinetic response (OKN) evoked by horizontal rotations of the optokinetic drum. VOR, VOR–OKN and OKN were evoked through a computer driven rotating chair and optokinetic drum (model "Rotomac", Megaris s.a.s.). The optokinetic drum had vertical black and white stripes each subtending 6° of the visual angle. Each stimulation (VOR, VOR–OKN, OKN) was given at two different velocities of rotation (peak velocities: 30 and 60°/s, frequency 0.05 Hz; corresponding average velocities: 15 and 30°/s). For each type of stimulation and velocity, ocular responses were recorded during two trials. Each trial consisted of two cycles of rotation which, following a

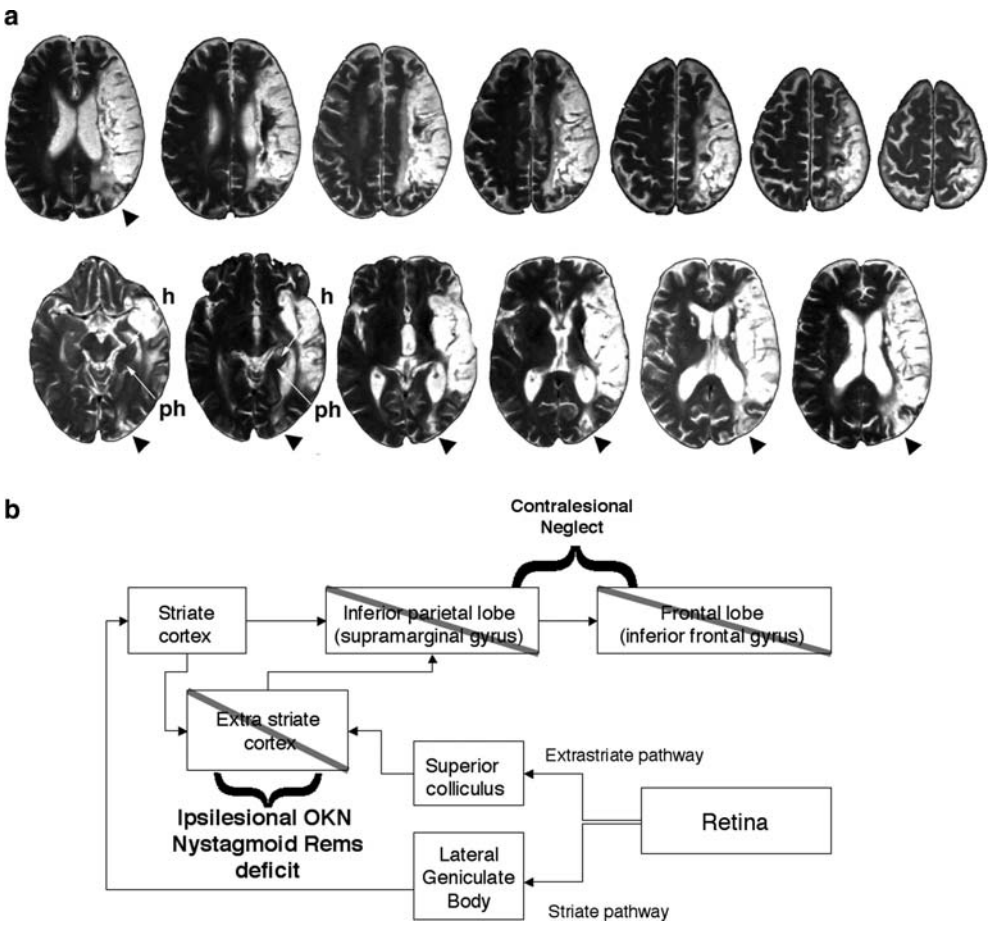


Fig. 1 **a** NMRI scans of the patient. Posteriorly, the lesion involves BA 19 and BA 37 (i.e. middle and superior occipital gyrus and the caudal part of the middle and superior temporal gyrus: these areas are indicated by *black arrows*). In the parietal lobe there was complete involvement of the supramarginal gyrus and partial sparing of the angular gyrus. The damage completely spared medial striate occipital cortex, medial temporal areas, the hippocampus (*h*) and the parahippocampus (*ph*). Anteriorly, the damage partially spared the frontal eye fields (BA 8). **b** Schematic diagram summarising the extrastriate circuit mediating OKN with rightward slow phases and the parietal–frontal circuit subserving representation of the left side of space in the right hemisphere. *Crossed boxes* indicate damaged areas, disturbances resulting from damage are reported near crossed boxes

sinusoidal velocity profile, alternated accelerations and decelerations in the two lateral directions. One of these trials started in the leftward direction and the other one in the rightward direction (see Fig. 2).

Exploratory saccades were recorded during a visual search task performed either in complete darkness or in a lit environment. Using Hornak's methodology (1992), the patient was asked to look for the appearance of a

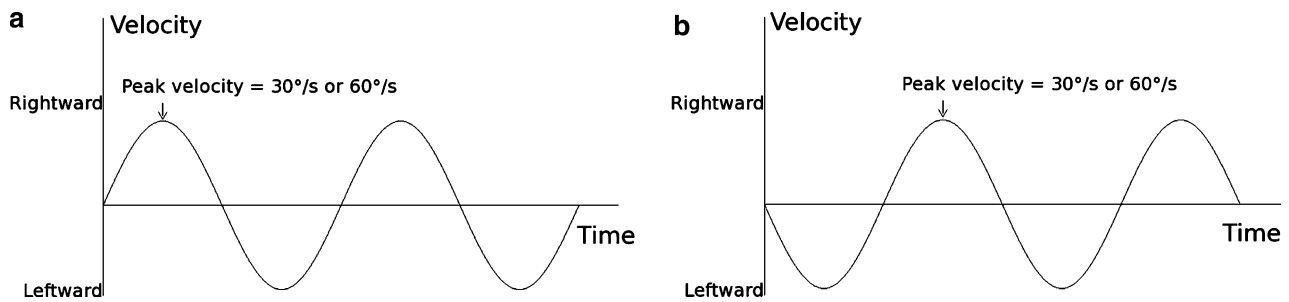


Fig. 2 Velocity profiles of VOR, VOR–OKN and OKN rotatory stimulations. **a** Trial starting in the rightward direction. **b** Trial starting in the leftward direction. On the *Y*-axis: positive velocity values = rightward turn, negative velocity values = leftward turn

red spot (diameter 5 mm, projected by a laser pointer) on a large screen (2 m × 1.5 m; distance from the patient = 1 m). For each experimental condition (darkness, light), two filler and two experimental trials were run. On filler trials, the spot was presented 10 s after the disappearance of the initial central fixation point (aligned to the head–body midsagittal plane), once in the left and once in the right hemifield at random positions. On each experimental trial, exploratory saccades were recorded for 20 s without presenting the red spot. Only saccades performed during experimental trials were considered in the analysis of data.

Oculomotor tasks were run with the patient seated in the rotating chair with the head blocked by an appropriate rest. A security belt, arms and legs straps further stabilized the patient's body during head body rotations.

Sleep study

The sleep of BQ was examined during three undisturbed nights: 7, 9 and 23 weeks after the stroke. EEG and EMG sleep recording was performed using standard procedures (Rechtschaffen and Kales 1968). Horizontal eye movements were monitored with AC unipolar derivations on nights 1, 2 and 3 (time constants: 0.1, 0.3 and 5 s). On nights 2 and 3, horizontal and vertical eye movements were also recorded with DC bipolar derivations (A/D sampling rate, 200 Hz).

The study was approved by the institutional ethics committee and was carried out according to the principles laid down in the Helsinki Declaration.

Results

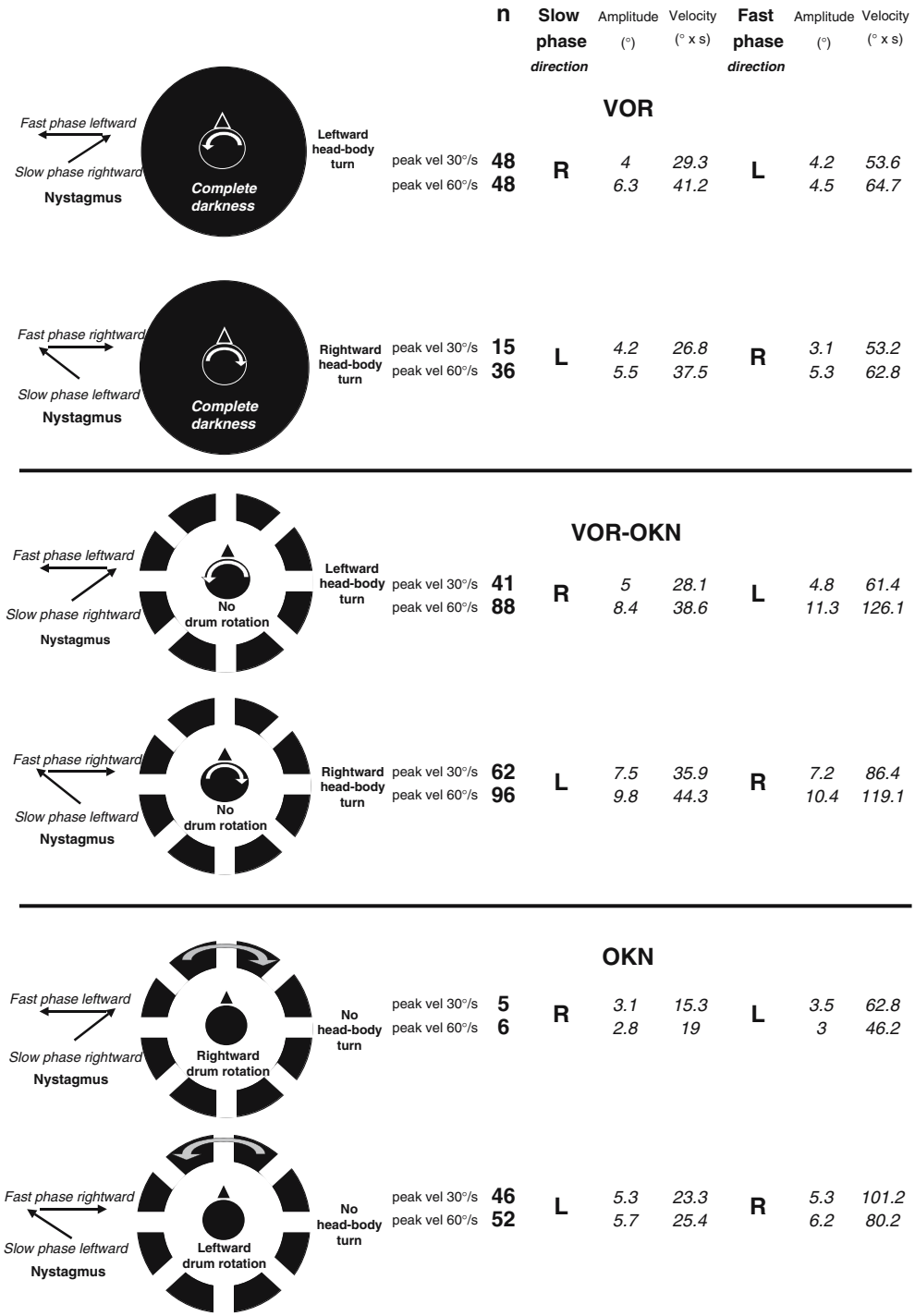
Waking eye movements

In line with a previous group study (Doricchi et al. 2002), the patient showed asymmetrical horizontal VOR with fewer alternating leftward slow/rightward fast phases (as compared with the frequency of alternating rightward slow/leftward fast phases) and reversed asymmetrical horizontal VOR–OKN with fewer alternating rightward slow/leftward fast phases (as compared with the frequency of alternating leftward slow/rightward fast phases; chi-square test, $P < 0.01$ for frequencies collapsed across velocities of stimulation and slow velocity; chi-square test, $P = 0.1$ for high velocity of stimulation; Table 1). Notably, BQ showed dramatic asymmetry of the horizontal OKN, with a drop in the frequency of alternating rightward slow/leftward fast phases (chi-square comparisons with VOR and VOR–OKN, $P < 0.0001$ at all velocities of stimulation; Table 1).

During exploratory tasks, the patient performed an equivalent number of leftward and rightward saccades (see Table 2) both in darkness (leftward 20, rightward 21) and in light (leftward 37, rightward 41; side x condition, chi-square not significant). In both conditions, ocular fixations were biased toward the right ipsilesional space (Table 2; unilateral brain damaged patients without neglect do not show this kind of spatial shift; Hornak 1992). The average rightward ipsilesional shift of saccadic fixations tended to be more accentuated in light (13.4°) as compared with darkness [8.5°; F (1, 120) = 3, $P = 0.08$]. Saccadic amplitudes (Table 2) were entered in an experimental condition (darkness, light) × saccade direction (leftward, rightward) ANOVA. This showed no significant effect or interaction, although rightward saccades performed in light tended to be ampler (16.7°) than leftward saccades performed in light (11.6°) and rightward (11.3°) or leftward (11°) saccades performed in darkness ($P = 0.06$ in each comparison of the means). The same type of ANOVA run on saccadic velocities (Table 2), showed a significant condition effect [F (1,118) = 6, $P = 0.01$] and a close to significance condition × saccade direction interaction [F (1, 118) = 2.2, $P = 0.10$]. Saccades performed in light were faster (162°/s) than those performed in darkness [125.8°/s; F (1, 118) = 6.4, $P = 0.01$]. Comparisons of the means showed that rightward saccades performed in light were faster (185°/s) than all of the other saccades (leftward light = 140°/s, rightward darkness = 126°/s, leftward darkness = 125°/s; $P < 0.05$ in each comparison).

To summarize, right brain damage produced two main alterations in the waking oculomotor behaviour of BQ. The first was a shift in the average position of saccadic fixations toward the right egocentric space, with no lateral imbalance in the frequency of saccades directed to the relative left or relative right of fixations (absence of lateral imbalance was probably linked to partial sparing of frontal eye fields, BA 8, in the damaged hemisphere, see Fig. 1a). The second was a severe impairment of the slow phases of the OKN in the rightward direction and of corresponding alternating fast phases in the leftward direction. The counterintuitive contrast between pathological rightward bias in saccadic inspection and impaired rightward slow oculomotor tracking is entirely explained by the fact that damage to parietal–frontal areas in the right hemisphere causes defective saccadic inspection of the contralesional left hemispace (Hornak 1992) whereas damage to lateral extrastriate areas (BA 19 and 37) of the same hemisphere disrupts smooth oculomotor tracking and the

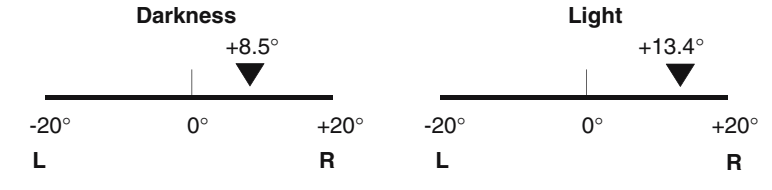
Table 1 Leftward and rightward frequencies, amplitude and velocity of the slow and fast phases of the VOR (head–body rotations in darkness), the combined VOR–OKN (due to rotations within the lighted optokinetic drum) and of the OKN (due to rotations of the optokinetic drum)



slow phase of the OKN in the ipsilesional direction (Baloh et al. 1980; Barton et al. 1996; Incoccia et al. 1995). As a result, extended right brain damage involving both the parietal–frontal and the extrastriate areas, such as BQ's, causes directionally opposed impairments of saccadic inspection and slow OKN eye movements. Damage to these two different circuits is summarised in the schematic diagram reported in Fig. 1b. Here, it is also important to remind that although final brainstem oculomotor commands are the same both for the

Table 2 **a** Average fixation position (in °) during visual search performed in darkness or light; **b** frequency, amplitude and velocity of leftward and rightward saccades performed in darkness or light

a



b

	Darkness			Light		
	n	Amplitude (°)	Velocity (°)	n	Amplitude (°)	Velocity (°)
Leftward saccades	**20**	11	125	**37**	11.6	140
Rightward saccades	**21**	11.3	126	**41**	16.7	185

saccades and for the fast phases of the OKN, there are important differences in the premotor events that trigger these two types of eye movement (Ilg 1997). Saccades are strongly dependent on foveal vision and the phylogenetically recent expansion of the geniculo-striate pathways. On the contrary, OKN can be triggered by global environmental motion, independent of foveal vision. In adult foveate vertebrates such as cats, monkeys and humans, the processing of global motion that feeds the OKN importantly depends on the extrastriate cortex (middle temporal and middle superior temporal cortex; Ilg 1997), which receives relevant input from the phylogenetically older tectofugal retinal-collicular pathway (Rafal et al. 1991; Aboitz et al. 2003).

Sleep study

On average, on each of the three nights BQ spent 382 min in NREM sleep (SD 56 min) and 109 min in PS sleep (SD 28 min).

REMs

Analysis of eye movement dynamics preceding and following REMs during PS, revealed the presence of morphologically distinct and previously unnoticed or not systematically described types of REMs. The first type (Fig. 3a), labelled "*Single step-REMs*", was made up of single REMs followed by a staring ocular position. These have been incidentally noted in a number of studies in humans (Reding and Fernandez 1968; Jacobs et al. 1972; Salzarulo et al. 1973; Schneider 1978) and cats (Vanni-Mercier et al. 1994). The second type (Fig. 3b), labelled "*Staircase-REMs*", were REMs immediately followed by other REMs in the same direction with barely detectable periods (i.e. below 150 ms) of stable fixation between them. These were occasionally noted in humans (Jacobs et al. 1972; Salzarulo et al. 1973; Schneider 1978), monkeys (Fuchs and Ron 1968) and in cats (Vanni-Mercier et al. 1994). The third type (Fig. 3b), labelled "*Loop-REMs*", were REMs followed with no pause by REMs in the opposite direction: this type of REMs has been described in humans (Salzarulo et al. 1973; Schneider 1978), monkeys (Fuchs and Ron 1968) and cats (Vanni-Mercier et al. 1994; several authors also suggested that this types of REMs never occurs in waking). The fourth type (Fig. 3c), labelled "*Nystagmoid-REMs*", were REMs regularly alternating with slow eye movements in the opposite horizontal direction. Nystagmoid REMs have been described in normal humans (Dement 1964; Reding and Fernandez 1968; Kawahara et al. 1980; Eisensehr et al. 2001), in patients with central and peripheral neural pathologies (Appenzeller and Fischer 1968; Tauber et al. 1973; Kawahara et al. 1980; Gordon and Oksenberg 1993; Eisensehr et al. 2001), in cats with partial unilateral lesions of the vestibular nuclei (Perenin et al. 1972) and in the intact cat (Vanni-Mercier et al. 1994). Although not emphasised by the authors, nystagmoid REMs are also visible in the EOG tracings reported in a study in intact monkeys (Zhou and King 1997).

Crucially, as with waking OKN, Nystagmoid-REMs with alternating rightward slow and leftward fast phases were virtually absent. The other types of REMs did not show comparable directional asymmetry (Table 3). Frequency asymmetry of Nystagmoid-REMs was significantly stronger as compared with each of the other types of REMs (chi-square test, $P < 0.0001$ in each comparison). There was no significant difference in the frequency of the different types of REMs between night 2 and 3 (chi-square test, ns). Amplitude and velocities of leftward and rightward REMs were entered in a REMs Type (Single step, Staircase, Loop, Nystagmoid-Fast phases) × Direction (leftward, rightward) ANOVA. Independently of Type, rightward REMs were ampler [F (1, 2426) = 4.6,

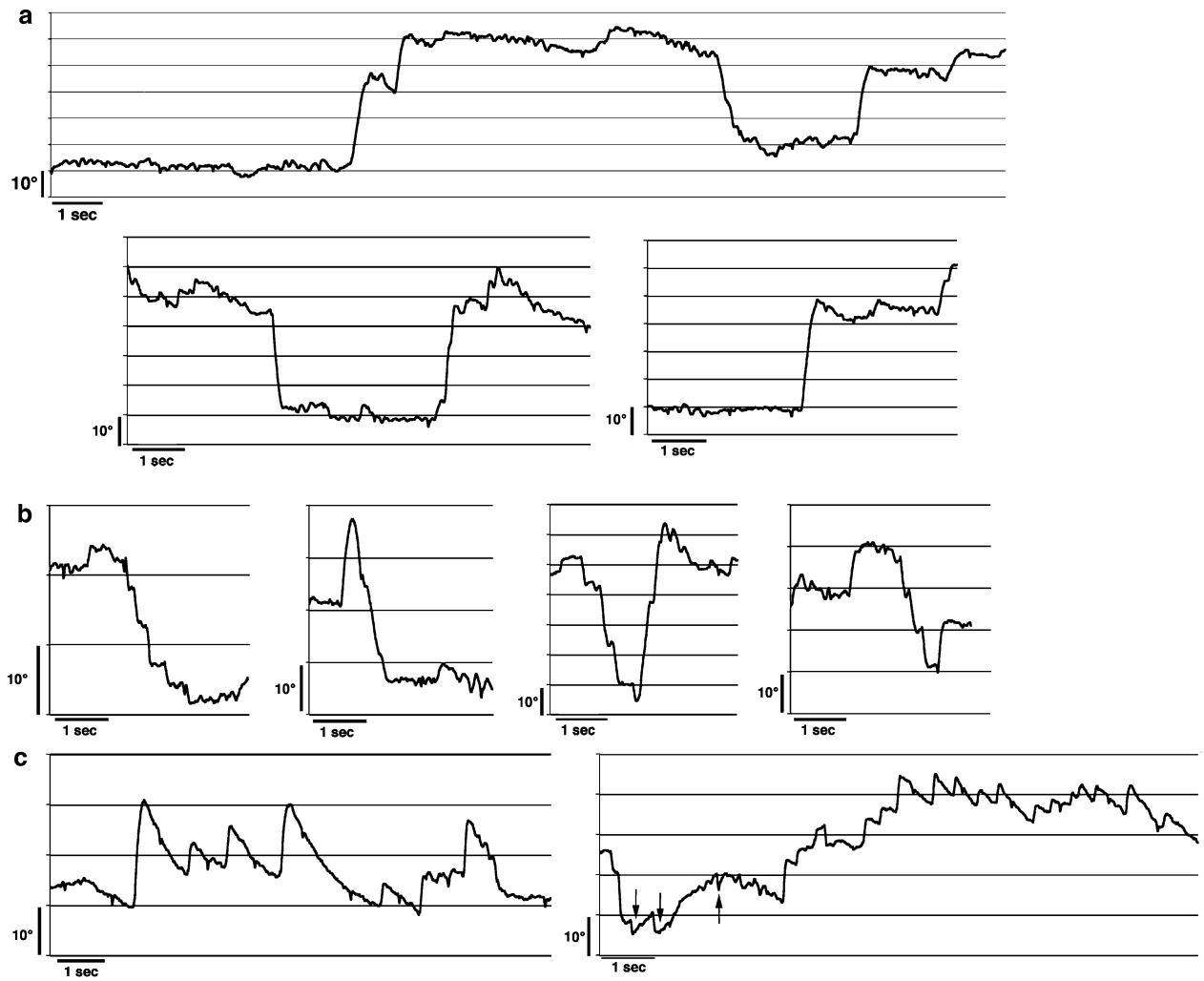


Fig. 3 Examples of the different types of REMs (night 2 and 3, DC-EOG recording; upward deflections of the tracing = rightward, downward deflections = leftward). **a** "Single step REMs". **b** "Staircase REMs" and "Loop REMs". **c** "Nystagmoid REMs": the only three "Nystagmoid REMs" with rightward slow/leftward fast phases found in the EOG recordings, are indicated by *arrows* in the second tracing

$P = 0.03$] and faster [F (1, 2426) = 18, $P < 0.001$] than leftward ones. No velocity difference was found among the different types of REMs ($F = 1$).

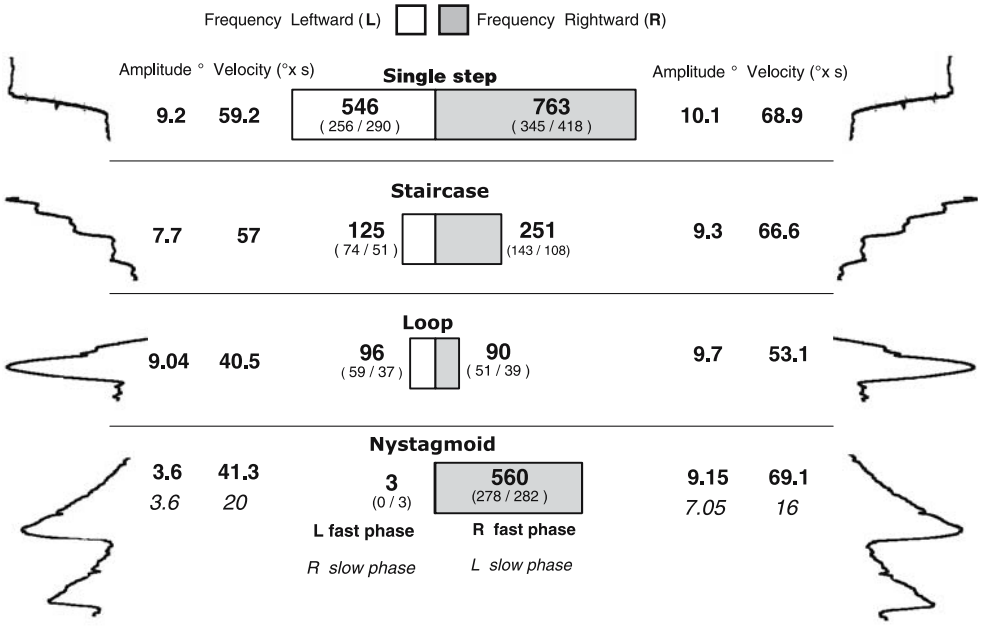
The velocity of the fast phases of Nystagmoid-REMs was compared to that of the fast phases of the VOR, VOR–OKN and OKN through a Type of eye movement × Direction (leftward, rightward) ANOVA. This showed that both Nystagmoid REMs and the fast phases of the VOR were slower than the fast phases of the VOR–OKN and the OKN (Type of fast phases: main effect F (3, 1098) = 26, $P < 0.001$; planned comparisons, $P \leq 0.01$). The velocity of Nystagmoid REMs was equivalent to that of the fast phases of the VOR elicited in darkness (planned comparison, P ns). It is worth noting, however, that although their velocity was the same, Nystagmoid REMs and VOR had directionally opposed horizontal frequency asymmetries, with REMs asymmetry equivalent to that of the OKN. This shows that similarity of velocity does not necessarily reflect similarity of underlying neural control and this in turn, calls for caution in basing conclusions exclusively on comparison of velocity or amplitude/velocity relationship of REMs and saccades.

Independently of horizontal direction, explorative saccades were generally faster than all types of REMs, (main effect of Eye movement type (Saccades, REMs type) × Direction (leftward, rightward) ANOVA, $P < 0.05$ in all separate comparisons between Saccades and each type of REMs). This agrees with findings from previous studies (Jeannerod and Mouret 1962; Herman et al. 1983).

Dreams

Patient's dream reports showed a remarkable congruency between the directional asymmetry of Nystagmoid

Table 3 Total leftward and rightward frequencies (night 2 and 3, DC-EOG recording) of the different types of REMs with corresponding mean amplitude and velocity



Frequencies from night 2 and 3 are reported in brackets below total frequencies. Examples of the different types of REMs with leftward and rightward fast phases are reported, respectively, to the left and to the right of corresponding frequency, amplitude and velocity values. Note that in the case of Nystagmoid REMs, fast phases in one direction (L or R) correspond to slow phases in the opposite direction. On night 1 (AC-EOG recording), 581 rightward and 171 leftward REMs were recorded

REMs and the visual events in the dream scene. On night 2, BQ spontaneously woke up at the end of a PS phase with bursts of Nystagmoid-REMs with leftward slow and rightward fast phases and reported a dream in which he was in a railway station waiting for somebody and facing a train travelling along the track in the leftward direction. At the end of night 3, in response to general inquiry on the quality of his night of sleep, BQ reported another dream in which he was driving his car and looking through the window on his left side at the landscape flowing leftward. In the same dream he showed a fluctuating level of awareness of motor impairments he perfectly acknowledged in waking. At the beginning of the dream, he described himself getting out of the door on the left side of the car, meeting a friend and saying to him that he had fully recovered from hemiplegia. At the end of the same dream he described himself saying to another friend that he could run "but not as well as before yet".

Discussion

As reported in the Results section, different authors have anecdotally noted morphologically different REMs. In this study we specifically identify the existence of these types of REMs and suggest, for the first time, a labelling and classification system for them. The existence of different types of REMs opens up interesting, new perspectives on dream and sleep research. For example, imaging and psychophysiological studies could further clarify the neural correlates of the different types of REMs and specify their possible correspondence with specific visual-spatial features in the dream scene. One might also ask whether differentiating the types of REMs can improve the sensitivity of important parameters of sleep efficiency used in sleep medicine such as "REM density" (i.e. the number of REMs per minute of PS).

Importantly for our findings, different authors have identified and described nystagmoid activity during PS in normal human subjects (Dement 1964; Kawahara et al. 1980; Eisensehr et al. 2001) and in the intact cat (Vanni-Mercier et al. 1994). It is also worth mentioning that in normal humans, optokinetic stimulation prior to sleep seems to influence the production of REMs during subsequent PS phases (De Gennaro and Ferrara 2000). The presence of stimuli evoking OKN, like travelling in or looking at running vehicles or moving objects, is also frequent in dream settings (Porte and Hobson 1996). The first dream reported by our patient, in which he was waiting for someone on the side of the

railway track and facing a train running leftward, has striking formal and perceptual analogies with a famous series of dream reports described by Hobson (1988; the dream diary of the "Engine man": see in particular the dream of the railway station from July 28 to 29 reported in the bottom part of Fig. 11.2, page 24, and the drawings of running trains on Fig. 11.1, page 237). The second dream reported by our patient, in which he was driving his car and looking at the landscape through the window on his left side, has also significant analogies with pioneering observations by Roffwarg and Muzio, which first established a relationship between the spatial organisation of the dream scene and OKN-like activity in PS (reported by Dement 1964). These authors described a normal subject who, when awakened from a PS phase with bursts of ocular nystagmus with rightward slow/leftward fast phases, reported a dream in which he was sitting on the right side of a running subway wagon and looking through the window on his right side at the landscape flowing in the rightward direction. In line with this observation, one would predict that a brain lesion suppressing OKN in one horizontal direction might also affect Nystagmoid-REMs in the same direction, producing specific effects on the spatial organisation of the dream setting and the way the attention of the dreamer is deployed in the dream scene (Schwartz and Maquet 2002). This is precisely what we found in our patient. Our case study also shows that a unilateral brain damage can completely suppress Nystagmoid-REMs in one horizontal direction leaving other types of REMs relatively unaffected. This suggests, for the first time, that in humans morphologically different types of REMs exist and shows that, of these types, Nystagmoid-REMs are driven by distinct premotor mechanisms. The concomitant drop in the frequency of nystagmoid-REMs and waking OKN in the same horizontal direction challenges the idea that REMs depend exclusively on brainstem mechanisms selectively activated during PS (Hobson and McCarley 1977).

Posteriorly, BQ's brain damage involved Brodmann's areas (BA) 19 and 37 in the lateral extrastriate cortex and the posterior limb of the internal capsula. Unilateral lesions of these structures disrupt motion perception, smooth pursuit and the slow phase of the OKN in the ipsilesional direction (Baloh et al. 1980; Barton et al. 1996; Incoccia et al. 1995). In the case of BQ, the lesion also suppressed Nystagmoid-REMs with the slow phase in the ipsilesional direction: as a consequence, the striking prevalence of leftward slow Nystagmoid-REMs shifted the gaze and attention of the dreamer towards the contralesional side of the dream scene. This effect is remarkably similar to the improvement of attention for the contralesional left side of space, which is induced in patients with left unilateral neglect by optokinetic stimulation directed leftward (Pizzamiglio et al. 1990). It is also worth noting that extrastriate areas involved in the control of the slow phases of the OKN (BA 19 and BA 37) are specifically activated by PS (Braun et al. 1998) and that their activation is correlated both with the frequency of REMs (Braun et al. 1998) and the activation of the hippocampus (Maquet et al. 1996; Braun et al. 1998). Correspondence between direction of the slow phases of Nystagmoid REMs and direction of attention in the dream scene, might therefore suggest that extrastriate activity related to REMs reflects changes in the attentional salience of the spatial and topographical features in the dream scene. These features are likely to be processed in medial temporal-hippocampal networks, as demonstrated by sparing of these structures with preserved topographical memory and dreaming in our patient BQ and by complete loss of dreaming in patients with medial occipital-temporal lesions and topographical disorientation (i.e. Charcot-Wilbrand syndrome; Doricchi and Violani 1992; Solms 1997; Bischof and Bassetti 2004).

Toward an evolutionary account of dream bizarreness

Our previous studies of neglect patients documented dissociation between complete suppression of leftward REMs during PS (Doricchi et al. 1993, 1996) and equivalent frequency of rightward and leftward waking saccades during visual search which, as in the present case study, was pathologically shifted toward the ipsilesional space. This demonstrated that scanning at the dream scene in PS is not equivalent to voluntary self-paced saccadic visual search. By contrast, this study shows drop of OKN and Nystagmoid-REMs with rightward slow/leftward fast phases both in waking and PS thus suggesting that reflexive and phylogenetically ancient oculomotor mechanisms such as the OKN, which is the smooth pursuit-orienting response of afoveate animals (Robinson and Zee 1981; Ilg 1997), are shared by waking and PS. Several lines of evidence support this suggestion. Sharing of phylogenetically ancient orienting mechanisms by waking and PS was first suggested by Bowker and Morrison (1976) who demonstrated that, on waking, only reflexive eye movements linked to the startle-orienting response are coupled with phasic ponto-geniculate-occipital waves (PGO) typically accompanying REMs during PS (Datta 1997). Further evidence that phylogenetically recent oculomotor mechanisms are incompletely activated during PS comes from studies of binocular coordination of eye

movements. Binocular coordination favours stereopsis and reaches its full evolution in animals with frontally placed eyes. It is poorly developed or undeveloped in animals with lateral eyes (King and Zhou 2000). Zhou and King (1997) found that in animals with frontal vision like monkeys, binocular coordination is disrupted during PS, as if in primates PS resets oculomotor commands on the operating mode of animals with lateral vision. Disjunctive REMs were also documented in normal humans (Gabersek and Scherrer 1969).

In humans, the preferential activation of less recently evolved neural structures during PS is not limited to oculomotor commands. Neuroimaging studies show that the lateral extrastriate cortex, which is the main recipient of the phylogenetically older tectofugal retinal-collicular pathway (Rafal et al. 1991; Aboitz et al. 2003), is tonically activated during PS (Maquet et al. 1996; Nofzinger et al. 1997; Braun et al. 1998). Similarly, a network of structures derived from archi and paleocortex comprising the hippocampus, the amygdala, the ventral anterior cingulate and the mesolimbic orbitofrontal cortex is also tonically activated during PS (Maquet et al. 1996; Nofzinger et al. 1997; Braun et al. 1998). At the same time, the striate visual cortex, which is the main recipient of the phylogenetically recent retinal-geniculate pathway (Rafal et al. 1991; Aboitz et al. 2003), is tonically deactivated, showing only phasic responses putatively linked to PGO waves (Peigneux et al. 2001). Most importantly, recently evolved areas such as the parietal polymodal and the dorsolateral prefrontal cortex are tonically deactivated in PS. Deactivation of the lateral prefrontal cortex, has been specifically linked to executive impairments in dreaming, such as spatial-temporal disorientations, illogic, impaired working memory with amnesia for dreams, misidentification of characters and locations and, as in the very case of BQ's dreams, anosognosia (Doricchi and Violani 1992; Schwartz and Maquet 2002; Pace-Schott and Hobson 2002).

In summary, much of the evidence suggests that PS preferentially activates evolutionary ancient brain structures. We now propose a new evolutionary account of dream bizarreness that might also provide a likely explanation for patterns of brain activation found during PS in humans.

An evolutionary hypothesis

In mammals such as the rat, which have relatively less expanded neopallial structures compared to humans, PS induces ordered sensory-motor replay of episodes of waking environmental exploration in the place cells of the hippocampus (Pavlides and Winson 1989; Louie and Wilson 2001). This ordered replay seems in sharp contrast with the pervasive and bizarre spatial and temporal incongruities characterising dreaming during PS in humans. Here, we hypothesise that in humans PS fails to faithfully replay complete and integrated waking episodes (Schwartz 2003), because it is originally attuned to orderly reactivation of phylogenetically ancient sensory, motor and memory networks whereas it is not sufficient for orderly reactivation of more complex and phylogenetically recent networks underpinning episodic memories in humans (Burgess et al. 2002). We believe that this inadequacy might have its evolutionary roots in the sensory and motor isolation from the environment, resulting from active blockade of afferent sensory input and efferent motor output, which characterises the functioning of the nervous system during PS (Vertes 1984). We argue that due to evolutionary acquisition of sensory-motor isolation (whatever the primary biological advantages provided by isolation might be; Siegel 2005) brain networks endogenously re-activated by PS could not undergo any further significant biological evolution. By contrast, sensory, motor and memory networks activated during waking underwent further evolution because of the very interaction of the organism with the environment. Thus, in the human brain, the endogenous and ordered re-activation of phylogenetically ancient brain networks during PS might result in incomplete or haphazard re-activation of more phylogenetically recent networks ensuring adaptive and flexible orientation in space and time during waking. We propose that dream bizarreness in PS might importantly derive from this mismatch.

Some implications of our hypothesis could be empirically tested. For instance the similarity of oneiric motor and exploratory activity in PS with corresponding activity from the period of waking preceding sleep, could be investigated in different animal species by eliminating muscle atonia in PS. Another area of future investigation is the question of whether the similarity of brain activations in waking and PS (whether general or limited to specific neural systems), is stronger in organisms which, in the same class, have poor development of phylogenetically recent brain traits compared with organisms that have high development of the same traits (for example, mammals with poor or high development of the geniculate-striate pathway).

Conclusions

It has been suggested that deactivation of primary sensory and heteromodal association areas "at either end of the visual hierarchy mediating interaction with the

world" might favour isolation of the organism from the environment during PS (Braun et al. 1997). Our evolutionary hypothesis sees these deactivations as evolutionary effects that might cooperate with more peripheral inhibitory mechanisms providing sensory and motor blockade during PS (Vertes 1984). The same evolutionary interpretation also explains the seeming discrepancy between ordered reactivation of hippocampal place cells during PS in mammals with relative low expansion of the neopallium and the spatial-temporal bizarreness of dreams during PS in humans. This might offer a new, more comprehensive and physiologically plausible account than theories attributing dream bizarreness to "moral censorship" (Freud 1990), to intrinsically random brainstem bombardment of the cortex (Hobson and McCarley 1977) or to "unconstrained parietal-lobe mechanisms operating in reverse" (Solms and Turnbull 2002). We conclude that PS should no longer be merely considered a separate "third" behavioural state as compared to waking and quiet sleep: rather, the evidence from this and previous studies suggests that PS could be better understood as originating from a vestigial state of active waking which has been phylogenetically deprived of its overt interaction with the world.

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