Vestibular and muscular proprioceptive contributions to corporeal and spatial representations

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Self attribution
 ownership

Self orientation

Self localization
 embodiment

Golconde, René Magritte, 1953
The Menil Collection, Houston, Texas
Corporal and spatial representations

SENSORY CUES
- vestibular
- somatosensory
- visual

PROPRIORECEPTIVE CUES

CENTRAL REPRESENTATIONS
- Gravitational reference frame
- Egocentric reference frame
- Allocentric reference frame

THE BODY IN SPACE

REFERENCED ACTIVITIES
- Postural orientation and stabilization
- Locomotion Spatial navigation

Slides by Ch. Lopez [2007]
Corporeal and spatial representations

Sherrington proposed a taxonomy of sensations (1890’s, 1906):

- **Exteroception**: sight, taste, smell, touch, hearing
- **Interception**: vegetative, internal somesthetic sensations
- **Proprioception**: the ability to “feel our body as proper to us, as our property, as our own”.

- **Kinesthetic sense** (kinesthesia, sense of movement)
  - muscular, tendinous, articular receptors

- **Vestibular sense** (sense of balance, equilibrium)
  - inner ear (vestibular system)

EGOCENTRIC REFERENCE FRAME

GEOCENTRIC REFERENCE FRAME

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Part 1:

Vestibular contribution to spatial orientation
Vestibular contribution to spatial orientation

1. Introduction

- The vestibular system contributes in building up the representation:
  - Of the egocentric reference frame
  - Of the geocentric reference frame

The geocentric model of the universe: the Earth is at the center of the universe and the Sun and other objects go around it.

Vestibular system … Where are you? Who are you?

2. Vestibular system

a) The labyrinth

Otolithic system:
  - utricle
  - saccule

→ linear accelerations
  (gravity; gravito-inertial forces)

3 semi-circular canals:
  - anterior
  - posterior
  - horizontal (lateral)

→ angular accelerations

The labyrinth

Inner ear
Vestibular contribution to spatial orientation

2. Vestibular system … Where are you? Who are you?

b) The otolithic system: utricle and saccule

Utricular and saccular maculae are specialized in coding linear displacement of the head & static head tilt.
Vestibular contribution to spatial orientation

2. Vestibular system ... Where are you? Who are you?

c) The semicircular canals

Purves et al., 1999

3 orthogonally oriented semicircular canals

Ampulla of the semicircular canals

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Vestibular contribution to spatial orientation

2. Vestibular system … Where are you? Who are you?

c) The semi-circular canals

In the ampulla of the semicircular canals hair cells are specialized in coding angular displacement of the head.

“Push-pull” principle in the semicircular canals

Summary

• The peripheral vestibular system (bilateral, symmetrical) consists on each side of:
  • 2 otolithic organs: the saccule (vertical) and the utricle (horizontal)
  • 3 orthogonally oriented semicircular canals (superior, posterior, horizontal)

• Otolithic organs contain a macula with hear cells sensitive to linear acceleration from gravitational (head tilt) or inertial (head translation) origin
  threshold detection \( \approx 10^{-3} \text{ to } 5 \times 10^{-3} \text{ G} \)

• Semicircular canals contain an ampulla with hear cells sensitive to angular acceleration of the head
  threshold detection \( \approx 0.1 \text{ to } 0.2 \text{ °/s} \)

• Hair cells perform a mechanoelectrical transduction based on the deflection of the stereociliae, decreasing or increasing the afferent firing

Slides by Ch. Lopez [2007]
3. Central vestibular pathways and vestibular functions

3.1 The vestibular nerve and the vestibular nuclei complex

4 vestibular nuclei:
- Superior VN
- Lateral VN
- Medial VN
- Descending VN

(see Barmack, 2003)

Hain and Hilman, 1994

3.2 Ascending and descending connections of the vestibular nuclei complex

Vestibulocortical system
- self-motion perception
- vertical perception
- spatial navigation …

Vestibulooptic system
- gaze stabilization

Vestibulo-spinal system
- body stabilization
- body orientation
- … postural control

Spinal cord

Vestibular nuclei

Oculomotor nuclei

Thalamus

3 a) The vestibular nerve and the vestibular nuclei complex

b) Ascending and descending connections of the vestibular nuclei complex
Vestibular contribution to spatial orientation
3. Central vestibular pathways and vestibular functions

b) Ascending and descending connections of the vestibular nuclei complex

**Vestibulo-spinal system**
- body stabilisation
- body orientation
- postural control

**Vestibulo-ocular system**
- gaze stabilization

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Bear et al., 1997

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**Vestibulo-cortical system**
- self-motion perception
- vertical perception
- spatial navigation...

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Lopez et al., 2007b

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Electrical cortical stimulation in epileptic patients

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Lopez [2007]
Vestibular contribution to spatial orientation

3. Central vestibular pathways and vestibular functions

b) Ascending and descending connections of the vestibular nuclei complex

Vestibulo-cortical system

- Self-motion perception
- Vertical perception
- Spatial navigation...

A network of cortical vestibular areas
- Caloric stimulation
- Galvanic stimulation
- Saccular stimulation (clicks 102 dB)
- Intracortical stimulation

Vestibular contribution to spatial orientation

4. Multisensory integration along the vestibular pathways

a) The vestibular nuclei complex is composed of multimodal neurons
4. Multisensory integration along the vestibular pathways

b) The vestibular cortex is a multimodal cortex

Vestibular contribution to spatial orientation

Cerebral representations for egocentric space

Functional-anatomical evidence from caloric vestibular stimulation and neck vibration

Lopez et al., 2005. In: Lacour M. (Ed)
5. Symptoms of vestibular deafferentation

**Vestibulo-cortical system**

**Vestibulo-ocular system**

**Vestibulo-spinal system**

**VESTIBULAR LOSS**

Unilateral vestibular neurotomy

**Treatment of Ménière’s disease**

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**PERCEPTIVE SYNDROME**

- subjective visual vertical
- acceleration perception
- spatial navigation

**OCULOMOTOR SYNDROME**

- spontaneous nystagmus
- static ocular cyclotorsion
- skew deviation
- vestibulo-ocular reflex

**POSTURAL SYNDROME**

- head tilt
- head and body stabilisation
- walking performances
Vestibular contribution to spatial orientation

Summary

• Primary vestibular afferents composed the vestibular nerve (part of the cranial nerve VIII) projecting to the vestibular nuclei complex in the brainstem.

• Second-order vestibular neurons project to the oculomotor nuclei (vestibulo-ocular system) to stabilize gaze (stabilization of the images on the retina).

• Second-order vestibular neurons project to the motor neurons of the spinal cord (vestibulo-spinal system) to control body posture in space (orientation and stabilization of the body).

• Second-order vestibular neurons project to the thalamus and subsequently to the vestibular cortex (vestibulo-cortical system). Vestibular cortex comprises the PIVC, TPJ, areas 2v, 3av, 6v, precuneus and inferior parietal lobule (areas 39 and 40) ... and hippocampus.

• There is a multimodal integration in the vestibular nuclei, in the thalamus and in the vestibular cortical areas: visual-vestibular-somatosensthesic integration.

• Vestibular loss induces postural, oculomotor and perceptive syndromes.

• Vestibular compensation involves sensory substitution mechanisms (by visual and somatosensory cues).

6. The vestibular system and spatial cognition

a) The vestibular system for postural stabilization and orientation:

• The vestibular system as « a goal-dependent Euclidean egocentric reference frame » (Berthoz, 1991).

• The head as an « inertial guidance platform » (Pozzo et al, 1990).
6. The vestibular system and spatial cognition

b) The vestibular system and the perception of the vertical: which way is up?

In weightlessness (cosmonauts in space flights, parabolic flight)
There is no concept of "up" and "down"
(Lackner, 1992; Kornilova, 1997; Lackner and Dizio, 2000)
Vestibular contribution to spatial orientation

6. b) The vestibular system and the perception of the vertical: which way is up?

Patients with peripheral vestibular loss
Ipsilesional tilt of the perceived vertical (Friedmann, 1970; Hallpike et al., 1976; Cuthbert et al., 1991; Bisadorf et al., 1996; Böhmer et al., 1996; Riordan-Eva et al., 1997; Vibert & Häsler, 2000; Lopez et al., 2006, 2007).

Brain-damaged patients with focal lesions
- Insular cortex (Brandt et al., 1994)
- Superior temporal gyrus (Brandt et al., 1994; Hegemann et al., 2004; Darling et al., 2003)
- Posterior parietal cortex, inferior parietal lobule (Darling et al., 2003)

Vestibular contribution to spatial orientation

6. b) The vestibular system and the perception of the vertical: which way is up?

Effects of the gravitational vertical on the perception of reversible figures (Yamamoto & Yamamoto, 2006)
6. b) The vestibular system and the perception of the vertical: which way is up?

Effects of the gravitational vertical on the perception of reversible figures (Yamamoto & Yamamoto, 2006)

Probability that the right side of the figure was regarded as up:

- In the upright condition, the probability of perceiving the right side of the figure as the upward direction was roughly 50%
- In the right-side-up lying condition, however, the probability that the right side of the figure was perceived as upward was 69.2%, which was significantly larger than that for the upright condition (p < 0.0001)
- In the left-side-up lying condition, the probability that the right side of the figure was perceived as upward was 38.5%, and was significantly smaller than that for the upright condition (p < 0.0001)

The direction opposite to the force of gravity tended to be perceived as the upward direction for these reversible figures.
6. c) The vestibular system and self-motion perception

Should an apparent movement be attributed to a movement of the body in space or to a movement of the visual environment with respect to the body?

Is it my body or the visual surrounding that is tilted???

Is it my body or the visual surrounding that is rotating or translating???

Piet Mondrian: New York City I, 1942
Musée d’art contemporain Georges Pompidou, Paris

Dichgans and Brandt, 1978

Circular optokinetic stimulation

VIDEONYSTAGMOGRAPHY

KINEMATIC ANALYSIS

SUBJECTIVE VISUAL VERTICAL

POSTUROGRAPHY

Lopez et al., 2003

Lopez et al., 2003

Lopez et al., 2003
d) The vestibular system and spatial navigation:

Walking performances

- Light + References
- Darkness

Walking performance of vestibular-defective patients before and after unilateral vestibular neuronotomy

- Healthy
- Lesioned

Regression on locomotor trajectory (cm)
d) The vestibular system and spatial navigation:

• Berthoz et al., Israël et al. (1987, 1989, 1993, 1997). « linear head displacement measured by the otoliths can be reproduced through the saccadic system »: the brain can derive linear displacement from vestibular information and store this information to produce a saccade to an imagined memorized target

• « Vestibular information enhances the ability to perform a planned trajectory incorporating whole body rotations when no visual feedback is available » (Glassauer et al., 2002)

Péruch et al., 1999; 2005:

• vestibular cues are necessary not only to ensure an accurate posturo-locomotor control but also to build up an internal representation of the environment and of the body navigation in space
• after vestibular loss spatial memory would be disorganized
**d) The vestibular system and spatial navigation**

Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans

A 17% volume loss in the hippocampus of bilateral vestibular loss patients (age- and sex-matched).

When tested with a virtual variant (on a PC) of the Morris water task BVL patients exhibited significant spatial memory and navigation deficits. These spatial memory deficits were not associated with general memory deficits.

**e) Some methods for stimulating the vestibular system**

1. **Electrical cortical stimulation**

2. **Caloric vestibular stimulation**

3. **Galvanic vestibular stimulation**

<table>
<thead>
<tr>
<th>Method</th>
<th>Physiology</th>
<th>Repsones, Phenomenology, Cognitive effects</th>
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</table>
| 1. Electrical cortical stimulation | Convective ampullopetal or ampullofugal endolymph flow stimulates mainly the horizontal semicircular canals, and to a less extent the anterior and posterior canals. Warm water is stimulating for the horizontal canals. | vestibulo-ocular reflex (Bárány, 1906; Aw et al., 1998, 2000; Peterka et al., 2004)  
vertigo, dizziness  
visual hallucinations (Kolev, 1995)  
depersonalisation and derealisation (Yen Pik Sang et al., 2006)  
neglect-like behavior (Karnath et al., 2003)  
impaired mental imagery (Mast et al., 2006)  
improvement of spatial- and verbal-memory (Bächtold et al., 2001) |
| 2. Caloric vestibular stimulation | Convective ampullopetal or ampullofugal endolymph flow stimulates mainly the horizontal semicircular canals, and to a less extent the anterior and posterior canals. Warm water is stimulating for the horizontal canals. | vestibulo-ocular reflex (Bárány, 1906; Aw et al., 1998, 2000; Peterka et al., 2004)  
vertigo, dizziness  
visual hallucinations (Kolev, 1995)  
depersonalisation and derealisation (Yen Pik Sang et al., 2006)  
impaired mental imagery (Mast et al., 2006)  
improvement of spatial- and verbal-memory (Bächtold et al., 2001) |
| 3. Galvanic vestibular stimulation | Convective ampullopetal or ampullofugal endolymph flow stimulates mainly the horizontal semicircular canals, and to a less extent the anterior and posterior canals. Warm water is stimulating for the horizontal canals. | vestibulo-ocular reflex (Bárány, 1906; Aw et al., 1998, 2000; Peterka et al., 2004)  
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visual hallucinations (Kolev, 1995)  
impaired mental imagery (Mast et al., 2006)  
improvement of spatial- and verbal-memory (Bächtold et al., 2001) |

PhD Class, 2007
f) The vestibular system and embodiment – effects of cortical vestibular stimulations:

Stimulating illusory own-body perceptions

The part of the brain that produces out-of-body experiences has been located.

*Olaf Blanke*, **Striphanie Ortigosa**, **Theodor Landis**, Margitta Seeck

From Blanke et al., 2004

<table>
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<th>Temporo-parietal junction</th>
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<td>Out-of-body experience</td>
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The vestibular system and embodiment – effects of caloric vestibular stimulations:

Depersonalisation/derealisation symptoms in vestibular disease

*Yen Pih Song, K. Joubert-Renaud, D A Green, A M Boosien, M A Groty


<table>
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<th>Table 4: Frequency of symptoms included in the Cox and Swinson depersonalisation/derealisation inventory (2002)</th>
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<tr>
<td>Depersonalisation/derealisation symptoms</td>
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<td>1. Feeling of unreality</td>
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<td>30. Feeling of unreality</td>
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Altered perceptions of the self and the environment are termed "dissociation phenomena" and include depersonalisation which is a subjective experience of unreality and detachment from the self.2 Depersonalisation is often accompanied by derealisation, the experience of the external world appearing strange or unreal; viewed by some as a distinct disorder or as a subset of depersonalisation.
Body segment ownership:

- In patients with somatoparaphrenia. Originally described by Gerstmann (1942), somatoparaphrenia is a delusional belief concerning the sense of ownership of body parts. It is the feeling that a limb is not belonging to the body itself but rather someone else or that someone else’s limb is belonging to oneself.

- This symptom is often combined with hemineglect and hemianaesthesia.

- Right temporo-parietal lesions

- Bisiach et al. (1991) “Remission of somatoparaphrenic delusion through vestibular stimulation” (left arm) – caloric vestibular stimulation (left cold)

Prior to vestibular stimulation:

Ex: Whose arm is this?
A.R.: It’s not mine
Ex: Whose is it?
A.R.: It’s my mother’s. I found it in my bed.

Immediately after vestibular stimulation:

Ex: Show me your left arm
A.R.: Here it is
Ex: Is this arm yours?

\[ \text{Slides by Ch. Lopez [2007]} \]

Whole body ownership:

- In neurological patients with autoscopic phenomena

h) The vestibular system and ownership

i) The vestibular system and the body schema – effects of caloric & galvanic vestibular stimulations:

- In neglect patients:
  vestibular caloric stimulation modifies corporal awareness of neurological disorders such as hemineglect, anosognosia and hemianaesthesia (Cappa et al., 1987; Vallar et al., 1993, 1998; Rode et al., 1998; Rorsman et al., 1999; Bottini et al., 2005)

- In paraplegic patients:
  vestibular caloric stimulation evokes phantom limb illusions below the injury level in patients with complete section of the spinal cord (Le Chapelain et al., 2001)

- In amputees:
  vestibular caloric stimulation evokes in all “phantom groups” a change in the perception of the phantom, while in the “no phantom group” they could evoke a transient phantom feeling (André et al., 2001)

\[ \rightarrow \text{Suggest a strong influence of the vestibular cues on the neural basis of the body schema / body representation (e.g. neuromatrix from Melzack, 1995)} \]

\[ \text{Slides by Ch. Lopez [2007]} \]
The vestibular system and the body schema – effects of caloric & galvanic vestibular stimulations.

Before caloric stimulation

After caloric stimulation

From Rode et al., 1996

Vestibular stimulation would play centrally by restoring the symmetry of the internal representation of egocentric space.

Vestibular contribution to spatial orientation

Summary

- The vestibular system allowed:
  - postural stabilization and orientation by acting as a goal-dependent Euclidean egocentric reference frame
  - representation of verticality, sense of orientation / spatial orientation (which way is up?)
  - distinction between self-motion and object-motion (self-attribution of movements of the whole body)
  - spatial navigation (body displacements can be coded by the vestibular system, an internal representation of space is created and displacements are stored) and spatial memory

- Artificial stimulations of the peripheral vestibular system are achieved by: caloric and galvanic vestibular stimulations

- Vestibular system would be involved in own-body cognition:
  - in embodiment (self-localization)
  - in body part and whole body ownership (self-attribution)
  - in corporeal awareness
  - in the body schema / body image

- Vestibular system is fundamental for own-body cognition since it is involved in egocentric representation (personal space, self-motion…) and in maintaining a coherent relation between the egocentric space and the extrapersonal space, certainly through the representation of an invariant egocentric reference frame

Slides by Ch. Lopez [2007]
Part 2:

Muscular proprioceptive contribution to spatial orientation

Slides by Ch. Lopez [2007]

Proprioceptive contribution to spatial orientation

1. introduction

The muscular proprioceptive cues and other proprioceptive receptors contribute in building up the representation of the egocentric reference frame, the "body schema", the "body image"
Proprioceptive contribution to spatial orientation

1. Introduction

- The sense of the relative configuration of the body is commonly referred to as the body schema.

2. What are the muscular proprioceptive and cutaneous receptors?

There are numerous mechanoreceptors distributed in the musculo-skeletal system and the skin contributing to the "kinesthetic" (sense of movement) and the "cutaneous" (sense of position) sensibility.

Muscle spindles, Golgi tendon organs, Articular receptors, Cutaneous receptors.
Muscles spindles are found in the skeletal muscles. Receptors density depends on the muscle function (high density in the fingers, neck and extraocular muscles). Each spindle comprises 2 to 10 muscle fibers (the intrafusal muscle fibers) enclosed within a sheath of conjunctive tissue.
a) Muscle spindle

- Primary and secondary endings discharge when the muscle is stretched (dynamic lengthening or static position) and become silent when the muscle is shortened.
- **Primary endings** are more sensitive to stretch (= **dynamic sensitivity**).
- **Secondary endings** are more sensitive to position (= **static sensitivity**).

![Dynamic sensitivity](image1)

![Static sensitivity](image2)

From Vedel and Roll, 1983

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a) Muscle spindle

- Experimental manipulation of muscle spindle proprioceptive feedback by **mechanical tendon vibration**.
- Microneurographic recordings from human sensory nerve (Valbo and Hagbarth, 1968; Roll and Vedel, 1962; Vedel and Roll, 1983; Roll et al., 1989):
  - Vibratory stimulus preferentially activates Ia afferent fibers (primary endings).
  - Response of primary endings is proportional to the stimulus frequency within the range 1-100 Hz.
  - Primary endings respond to weak amplitude stimulations applied with high frequency whereas secondary endings need high amplitude stimulations and respond to low frequency stimulations only.

![Response to stimulations](image3)

From Roll and Vedel, 1982

From Roll et al., 1989
b) Golgi tendon organs

- Golgi tendon organs are encapsulated mechanoreceptors present at the myo-tendinous and myo-aponeurotic junctions of skeletal muscles.
- Within the tendon organ capsule, the terminal branches of a large diameter Ib afferent fiber are intertwined with collagen fibers in continuity with tendon.
- The other end is connected with a fascicle of 5-25 muscle fibers.
- The contraction of the muscle fibers, exerting strain on the collagen fibers and causing deformation of sensory terminals, is the adequate stimulus of the tendon organ.
- The tendon organ has a very low threshold to the change in the muscle tension, so that a single fiber twitch can elicit a discharge from the receptor (see Jami, 1992).

From Horcholle-Bossavit et al., 1989

Slides by Ch. Lopez [2007]

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c) Articular receptors

- Ruffini corpuscles (articular caps.
- Golgi corpuscles (ligaments)
- Pacini corpuscles (capsules)
- Free nerve endings

Fig. 5,4. Responses of a single joint afferent associated with the interphalangeal joint of the thumb to sustained pressure and passive joint movements in each of the three axes of rotation: adduction (long arrow applied in plane of phalanx), flexion (short arrow and extension (upward or downward angle relative to the longitudinal axis of the phalanx). The responses were measured by using a three-dimensional coordinate system described previously (Fig. 2 in Stein et al., 1988). A, perceptual matching during quantification of the same joint afferent. The output monitored the perceived movements by flexing the interphalangeal joint of the contralateral thumb; changes in joint angle were recorded by a joystick and expressed as a change in joint position. The options in the lower two panels represent the vibration pattern (V), (1 Hz, 50 Hz, 50 Hz, delivered to the distal interphalangeal joint. In both examples the apparent latency to the stimulus is 200 ms.

From: ARTICLES, 1994, 29, 10-19

PERCEPTUAL RESPONSES TO MICROSTIMULATION OF SINGLE AFFERENTS Innervating Joint, Muscles and Skin of the Human Hand

By: GARY WASSMELLER, SIMON C. GARDENIA, AND DAVID BURKE
Proprioceptive contribution to spatial orientation

3. The proprioceptive pathways to the central nervous system

From Bear et al., 1997
Proprioceptive contribution to spatial orientation

Summary

• The sense of "statesesthesia" and "kinesthesy" depends on multiple mechanoreceptors distributed in the muscular (muscle spindles), tendinous (Golgi tendon organs) and articular (Ruffini corpuscles, Pacini corpuscles, free nerve endings) tissues as well as in the skin.

• Muscles spindles are sensitive to the length and the position of the muscle (static sensitivity) as well as to stretch applied to the muscle (dynamic sensitivity).

• Muscles spindles can be activated artificially by mechanical tendon vibrations (Ia fibers essentially).

• Somatosensory cues reach the primary somatosensory cortex (postcentral gyrus) via the dorsal column, the fasciculus gracilis and cuneatus, the dorsal column nuclei, the medial lemniscus and the thalamus.

4. Manipulating "kinesthetic" and "statesesthetic" sensitivity

Mechanical tendon vibration evokes segmental or postural kinesthetic illusionary movement in the direction of stretch of the vibrated muscle (Goodwin et al., 1972; Eklund, 1972; Bonnet et al., 1973; Lackner and Levine, 1979; Roll et al., 1986, 1989).

From Roll et al., 1986
Proprioceptive contribution to spatial orientation

4. Manipulating “kinesthetic” and “gestesthetic” sensitivity

Influence of the environmental context

In weightlessness

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The Pinocchio illusion

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Without any contact (and eyes closed): loss of sense of orientation

With tactile stimulation to the head (and eyes closed): A sense of orientation is restored, subjects feel upside-down

From Lackner, 2002

Slides by Ch. Lopez [2007]
Proprioceptive contribution to spatial orientation

4. Manipulating “kinesthetic” and “statesthetic” sensitivity

Complex “kinesthetic” illusions induced by hand vibrations (Roll and Gilhodes, 1994)

• Neck muscle vibration improved task performance, while TES and hand vibration had little or no effect.

• The effect of neck muscle vibration cannot be explained as arousal and activation due to unspecific sensory stimulation on the contralesional side of the body.

• The effect of neck muscle vibration on neglect is induced by the predominant activation of afferent Ia nerve fibres and their specific contribution to the central representation of egocentric space.
Proprioceptive contribution to spatial orientation

4. Manipulating “kinesthetic” and “statesthetic” sensitivity

Perceptual and oculomotor effects of neck muscle vibration in vestibular neuritis
Ipsilateral somato-sensory substitution of vestibular function

Displacement of the SVA in control subjects (n = 25) and in patients with vestibular neuritis (n = 25). A illustrates the horizontal displacement of the SVA during vibration of the right and left dorsal neck muscles for each of the 25 control subjects, arranged in descending order from ~10° to 0.1°. During vibration there was a horizontal displacement of SVA towards the side of stimulation in all control subjects. The maximal displacement was ~10° in controls. The difference in the displacement of the SVA between vibration of the right and left sides was small (~0.1–4°).

B shows the horizontal displacement of the SVA during vibration ipsilateral and contralateral to the vestibular lesion for each of the 25 patients, arranged in the same way as in A. During vibration there was a horizontal displacement of SVA towards the side of stimulation in all patients. The maximum displacement of the SVA was ~10° in patients during stimulation contralateral to the lesion. However, during stimulation ipsilateral to the lesion the maximum displacement of the SVA was much higher (up to 30°).
Proprioceptive contribution to spatial orientation

4. Manipulating “kinesthetic” and “statesthetic” sensitivity

Cortical correlates of illusory hand movement perception in humans: A MEG study

LaurentCarrier*, HervéFerreol*, PierreBonnafous, AntoineGhysels, DenisScheurer, Jean-YvesAzevin, Jean-PierreBell

- The supplementary motor area, M1 and the left angular gyrus were found active in the “illusion” condition only
- The posterior parietal areas as well as motor areas are involved in the arising of kinesthetic sensations

Proprioceptive contribution to spatial orientation

5. Contribution of the muscular proprioception to the sense of embodiment

Christina (27 years old)
- Acute polyneuritis affecting the sensory roots of spinal and cranial nerves
- Profound proprioceptive deficit from the feet to the head (no muscle, tendon and joint proprioceptive sense)
- Standing was impossible (unless she looked at her feet) and she can hold nothing in her hands (unless she looked at her hands)
- And she complained « I can’t feel my body. I feel weird – disembodied ».

“The disembodied lady” (Chapt. III) from Oliver Sacks (1985)
Proprioceptive contribution to spatial orientation

Summary

- Mechanical tendon vibration evokes kinesthetic illusions of body segments or of the whole body (disturbed self-localization).
- Kinesthetic illusions depend on multisensory integration, on the environmental constraints (tactile cues, vestibular cues).
- Muscular proprioceptive cues strongly contribute in building a central representation of an egocentric reference frame.
- Kinesthetic illusions are associated with activation in somatosensory and motor areas.
- Proprioceptive cues are fundamental for the sense of embodiment.

Golconde. René Magritte, 1953
The Menil Collection, Houston, Texas