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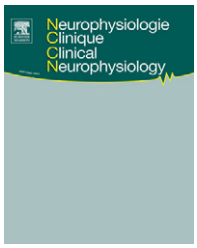

REVIEW/MISE AU POINT

Vertical frames of reference and control of body orientation

Référence verticale et contrôle de l'orientation corporelle

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MOTS CLÉS
Verticale subjective ;
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Summary The present paper aims at critically reviewing the most outstanding and recent studies regarding the control of body orientation in the vertical space. A first part defines the general concepts used throughout this manuscript. The second part investigates the vertical perception and the main factors which affect it, while trying to overcome the five areas of theoretical and experimental controversies we have identified in the literature. The third part of this review presents the different theoretical models of the vertical perception and body orientation in space. Finally, the last part focuses on the functional coupling between perception of the vertical and orientation of the body in space. It considers more particularly how these two dimensions interact for explaining the observed behaviors.
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Résumé Cette revue de question s'efforce de faire le point sur le contrôle de l'orientation du corps dans l'espace vertical en abordant de manière critique les travaux les plus marquants et les plus récents. Une première partie définit les principaux concepts abordés dans cette revue. Une deuxième partie explore la perception de la verticale et les principaux facteurs qui l'affectent, en tentant de résoudre un certain nombre de controverses théoriques et expérimentales repérées dans la littérature. Une troisième partie présente les différents modèles théoriques explicatifs de la perception de la verticale et de l'orientation du corps dans l'espace. La quatrième partie aborde finalement la question du couplage fonctionnel entre perception de

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Système vestibulaire ;
Système somesthésique ;
Posture ;
Gravité ;
Horizon subjectif

la verticale et orientation du corps dans l'espace. Elle envisage plus particulièrement comment ces deux dimensions interagissent pour expliquer les comportements observés.
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Introduction

Since Aubert [3] noticed that a vertical streak of light appears to tilt when the head is tilted in an otherwise dark room, this phenomenon has been extensively described and studied. Muller [97] named the effect described by Aubert [3], that the subjective vertical is tilted in the same direction as the true head tilt as the Aubert or A-effect. The Muller or E-effect is defined as the subjective vertical being tilted in the direction opposite to the head tilt. Howard and Templeton [51] provided a thorough review of the A- and E-effects and of the different conditions giving rise to them. However, new findings are still coming out, and the goal of this paper is to synthesize recent and classical results.

Before proceeding, it seems necessary to define the general concepts used throughout this manuscript. Some of the following concepts were inspired by the glossary of Lackner and DiZio [63], others by the introduction of Howard and Templeton [51].

Vertical—horizontal

In daily life, the vertical is the direction given by a plumb line perpendicular to the horizon and congruent with the gravitational acceleration. However, when the gravitational acceleration is reduced or even absent (e.g., in space flight), the vertical is perpendicular to the support surface. By extension, the horizontal plane is the plane perpendicular to the direction of the gravitational acceleration (when it is present). The horizon is the intersection between the earth and the sky seen by an observer.

Gravitational acceleration

The gravitational acceleration is the acceleration created by the force of gravity. Constantly pointing to the centre of the earth and with a magnitude of $9.81\,m{\cdot}s^{-2}$, it is an omnipresent feature that influences all animals' behaviors. When an animal is moving, its motion entails inertial accelerations that are combined with the gravitational acceleration. The resultant vector is the so-called gravitoinertial force (GiF, Fig. 1). Evidence has thus far confirmed Einstein's equivalence principle; no physical accelerometer can decompose the right side of the equation: GiF equals gravity plus the inertial force.

True and simulated tilt

True tilt refers to rotating an object relative to the gravity which should be equivalent to rotating the GiF relative to the object. The latter condition is called simulated tilt because, with respect to the gravity vector, the actual orientation of the object is not modified. It is possible to simulate tilt by centrifugation. When an object is spun in a centrifuge, out of the axis of rotation, a radial acceleration is produced, directed centrifugally and perpendicular to the gravity. The radial acceleration and gravity are summed producing a GiF resultant which rotates relative to objects fixed within the centrifuge (Fig. 1).

Planes and axes of rotation

We already defined the horizontal plane. However, when it refers to the human body we will speak about the midtransverse plane being the horizontal plane containing the body center of gravity (Fig. 2). Perpendicular to the midtransverse plane, the median plane segregates the right and left parts of the body in two equal parts. At the intersection of these two planes, there is the X-axis around which rotation in roll, right or left ear down, can be realized. Perpendicular to the midtransverse and median planes, the midfrontal plane segregates the front and the back of the body in two equal parts. Rotations in pitch, frontward or backward, are realized around the Y-axis which is at the intersection of the midtransverse and midfrontal planes. Finally, the intersection between the midfrontal and median planes defines the body Z-axis. Rotations around this axis are in yaw. Respecting the right hand rule, when the Z-axis points to the top or head, the X-axis points frontward and the Y-axis points leftward with respect to the subject's body. The idiotropic vector defined by Mittelstaedt [87—89] is a vector pointing up (or down [55]) and aligned on the Z-axis (see section: cognitive and observer models).

Egocentric and exocentric tasks

The axes just defined are egocentric because they refer to the subject's body. Setting a line parallel to the body Z-axis is an egocentric task. An exocentric direction or judgment

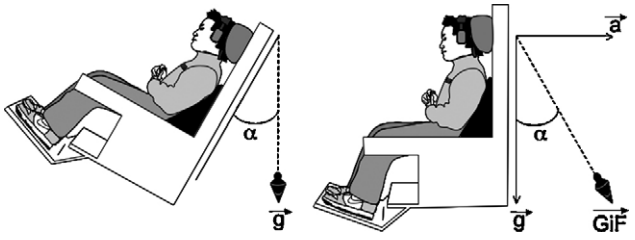

Figure 1 True pitch tilt versus simulated tilt by centrifugation.

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