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DIRECTION-DEPENDENT ACTIVATION OF THE INSULAR CORTEX DURING VERTICAL AND HORIZONTAL HAND MOVEMENTS

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Abstract—The planning of any motor action requires a complex multisensory processing by the brain. Gravity – immutable on Earth – has been shown to be a key input to these mechanisms. Seminal fMRI studies performed during visual perception of falling objects and self-motion demonstrated that humans represent the action of gravity in parts of the cortical vestibular system; in particular, the insular cortex and the cerebellum. However, little is known as to whether a specific neural network is engaged when processing non-visual signals relevant to gravity. We asked participants to perform vertical and horizontal hand movements without visual control, while lying in a 3T-MRI scanner. We highlighted brain regions activated in the processing of vertical movements, for which the effects of gravity changed during execution. Precisely, the left insula was activated in vertical movements and not in horizontal movements. Moreover, the network identified by contrasting vertical and horizontal movements overlapped with neural correlates previously associated to the processing of simulated self-motion and visual perception of the vertical direction. Interestingly, we found that the insular cortex activity is direction-dependent which suggests that this brain region processes the effects of gravity on the moving limbs through non-visual signals.

Key words: fMRI, gravitational force, hand movements, insular cortex, internal model.

INTRODUCTION

Gravity fundamentally affects the dynamics of all our everyday movements. Living beings have learned to live with gravity since time immemorial. Therefore, the CNS (Central Nervous System) has developed neural mechanisms to process gravitational acceleration in order to refine motor control and planning.

Biological sensors provide complementary signals that allow the brain to form an internal representation of gravity. Otoliths – which are linear accelerometers – respond identically during translational motion and gravitational acceleration. Remarkably, Angelaki and colleagues highlighted populations of neurons in monkeys which reflect the computations necessary to encode the physics of the external world (as gravity) in vestibular nuclei and cerebellar neurons. In particular, the neural activities of cells of the rostral vestibular nuclei and the fastigial nucleus of the cerebellum revealed processed rather than sensory-like, motion information (Angelaki et al., 1999, 2004; Angelaki and Dickman, 2000). This provides clear evidence that the action of gravity on otoliths allows the CNS to define the vertical direction on body–limb joints prior to engage any action. Previous investigations showed that the mechanical effects of gravity on body motion are well anticipated, suggesting that humans optimize the effects of gravitational force on subsequent actions in a predictive, feedforward manner (Pozzo et al., 1998; Augurelle et al., 2003; Zago et al., 2005; Gentili et al., 2007; White et al., 2008; Gaveau et al., 2014). This strategy allows circumvent the uncompressible delays of feedback.

Vertical upward and downward limb movements show robust kinematic asymmetries (Papaxanthis et al., 1998a, 2005; Gentili et al., 2007; Gaveau and Papaxanthis, 2011). Bell-shaped velocity profiles reach their peak sooner in upward movements and later in downward movements, while the acceleration and deceleration phases have the same duration for movements performed in the horizontal plane. Further, theses asymmetries appear as early as 200 ms after movement onset

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Abbreviations: BOLD, blood oxygenation level-dependent; CNS, Central Nervous System; GLM, General Linear Model; HL, Horizontal movement with additional load; MNI, Montreal Neurological Institute; VL, Vertical movement with additional load.

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which clearly indicates feedforward control (Gaveau and Papaxanthis, 2011). As shown in altered gravity experiments, exposure in microgravity modifies this directional asymmetry which clearly confirmed a central integration of gravity effects in the dynamic planning process (Papaxanthis et al., 2005; Crevecoeur et al., 2009a, 2009b; White, 2015). The same authors also proposed that the CNS is able to control independently inertial and gravitational forces to optimize movement. Recently, it has been demonstrated that the specific temporal pattern of vertical limb and body displacements is the result of direction-dependent planning processes that minimize energy expenditure on Earth (Berret et al., 2008; Gaveau et al., 2014).

Besides these behavioral results, we still lack a general understanding of neural mechanisms that encode the interaction of our movements with the external environment. Recent seminal investigations showed that the visual processing of gravity activates in particular the insular cortex and the temporo-parietal junction (Indovina et al., 2005). These experiments demonstrated that the processing of visual motion of an object along the vertical direction depends on the expected effects of gravitational acceleration, i.e., the activation of an internal model of gravity, on massive bodies (Mcintyre et al., 2001; Zago et al., 2009; Moscatelli and Lacquaniti, 2011).

Most previous investigations addressed the complex question of the internal representation of gravity through visual stimuli presentation (Lacquaniti and Maioli, 1989; Mcintyre et al., 2001; Zago et al., 2004, 2009; Indovina et al., 2005; Zago and Lacquaniti, 2005). Whether this is the case, however, during arm movements remains still an open question. Is the insular cortex engaged during the performance of arm movements without visual control? Here, we specifically test how non-visual information contributes to the processing of an internal model of gravity through the activation of the insular cortex. Because gravity influences differently the dynamics of movements in vertical and horizontal directions, we asked participants to perform hand movements in both directions while lying in an MRI scanner. We predict the existence of areas dedicated to the processing of non-visual information when gravity affects the way the task is achieved. By contrasting brain activation in vertical vs. horizontal conditions, we expect to highlight direction-dependent brain activity dedicated to the non-visual processing of gravity.

EXPERIMENTAL PROCEDURES

Participants

Nineteen healthy participants (all males, 29.1 ± 5.8 years old, from 22 to 50 years, 180.7 ± 5.6 cm, and 76.5 ± 7.6 kg) volunteered for the experiment. None of them had history of neuromuscular or neurological disorders or any indication against an MRI examination. All were right handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). All experimental acquisitions were conducted during the same time slots between 8 pm and midnight. The entire experiment conformed to the Declaration of Helsinki and informed consent was obtained from all participants. The protocol was approved by the clinical Ethics Committee of the University Hospital of Dijon (registered number 2009-A00646-51).

Data acquisition

Data were acquired using a 3T Magnetom Trio system (Siemens AG, Munich, Germany), equipped with a standard head coil configuration. We used standard single shot echo planar (EPI) $T2^*$-weighted sequence in order to measure blood oxygenation level-dependent (BOLD) contrast. The whole brain was covered in 40 adjacent interlaced axial slices (3 mm thickness, TR = 3050 ms, TE = 45 ms, flip angle = 90°), each of which was acquired within a 64 × 64 Matrix (FOV was 20 × 20 cm), resulting in a voxel size of 3.125 × 3.125 mm.

Experimental design and fMRI paradigm

We adopted a block design paradigm that alternated periods of rest (10 scans) and periods of hand movements (10 scans) in two different conditions. Participants were lying on their back in the MRI scanner with their upper right limb elevated by 5 cm with small cushions. This prevented the right hand to become in contact with surrounding objects during hand movement recording sessions. In addition, the experiment was realized in the darkness to avoid particular visual stimulation. During the rest period, participants were instructed to remain quiet, still, and to keep their eyes open without thinking of anything in particular. Participants were carefully observed during this period to ensure that no movement was performed. During the task blocks, participants moved their hand either vertically or horizontally. We repeated rest and hand movements blocks four times in one recording session. Therefore, a total of 80 scans in each experimental condition realized during one session (4 × 10 scans at rest and 4 × 10 scans of hand movements) were recorded per participant. The order of sessions was counterbalanced across participants.

In a first session (Vertical condition), participants were instructed to perform hand flexions and extensions in the sagittal plane at comfortable pace. Their hand was in supine position (palm up) and their fingers released (Fig. 1A). In a second session, participants performed the same movements in the horizontal plane (Horizontal condition), palm inward (Fig. 1B). Importantly, both movements involved the same flexor and extensor muscles of the hand, which allowed us to rule out any biomechanical effect of muscle activity on the BOLD signal (Mendell and Florence, 1990; Hislop and Montgomery, 2002). On average, participants realized 9 (± 1.2) movements per block, which resulted in 36 movements for each experimental condition. The number of movements performed in the Vertical condition and in the Horizontal condition was not statistically different ($t_{18} = 0.396$; $p = 0.697$), eliminating any possible effect linked to the amount of motion.