Does self-recognition of one’s own fall recruit genuine bodily crisis-related brain activity?

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Abstract While bipedalism is a fundamental evolutionary adaptation that is essential for the development of the human brain, the erect body is always an inch or two away from falling. Although the neural substrate underlying automatic detection of one’s own body instability is an important consideration, there have thus far been few functional neuroimaging studies due to the restrictions placed on participants’ movements. Here, we used functional magnetic resonance imaging to investigate the neural substrate underlying whole body instability, based on a self-recognition paradigm that uses video stimuli consisting of one’s own and others’ whole bodies, depicted in both stable and unstable states. Analyses revealed significant activity in the brain regions that should be activated during genuine unstable body (physical) conditions: the right parieto-insular vestibular cortex, inferior frontal junction, posterior insula and parabrachial nucleus. We argue that these right-lateralized cortical and brainstem regions mediate vestibular information processing for detection of vestibular anomalies, defensive motor responding in which the necessary motor responses are automatically prepared/simulated to protect one’s body, and sympathetic activity as an alarm response during whole body instability.

Keywords: body, instability, fMRI, insula, PIVC, self

Human neural response to whole body crisis

Bipedalism is the fundamental evolutionary adaptation that sets hominids – and therefore humans – apart from other primates. The human body is arranged vertically, such that the head, trunk, legs, and feet, as well as their links in the neck, spine, pelvis, knees, and ankles, dynamically balance together to form an upright “antigravity pole”. Because these segments and their points of articulation are not fixed, and given that the downward force of gravity never stops, the erect body always exists an inch or two away from falling. Some of the most important brain systems are dedicated to the maintenance of balance against the pull of gravity, and to providing an online representation of where in space the body is located, via the integration of many different exteroceptive/interoceptive inputs (visual, auditory, vestibular, somatosensory, motor, visceral, and so on)1-5). The neural system for rapid detection of potential falls and corresponding automatic reactions to prevent such falls is very important for human beings, and such a system constitutes one of the most important functions of the body schema, the innate bodily representation system that provides a repertoire of motor functions for promoting survival at the most basic level. The body schema is a plastic and dynamic representation of the spatial and biomechanical properties of the body that is derived from multiple sensory inputs that interact with motor systems6-7), and comprises the automatic motor and postural schemata upon which non-conscious movements are based, although these schemata can enter into and support intentional activity8-10). Although investigation of the neural mechanism that prevents us from falling is important for improving our understanding of basic evolutionary brain structures that support survival, brain scanning technologies such as functional magnetic resonance imaging (fMRI) place major restrictions on participants’ movements and, thus, do not permit study of in-vivo brain activity during falls, near-falls, or other instances of body instability.

Self-recognition and shared representation

When we see another person’s bodily movements associated with emotion, we immediately know what specific movement is associated with a particular emotion. Darwin argued that emotions are adaptive in the sense that they prompt an action that is beneficial to the organism given its environmental circumstances11). A shared representation mechanism based on the body-schema is proposed as the basis for both action3,12-14), and emotion recognition15-16), suggesting an intrinsic link between the two. Moreover, self-stimuli show a perceptual advantage in

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visual recognition, at least when recognition of one’s own body is compared to that of someone else’s\textsuperscript{17-21}. These self-stimuli appear to recruit specific underlying neural substrates\textsuperscript{22-25}. Such findings indicate that one’s own body sustains a distinct internal representation and that the perception-action matching system is optimally tuned for the observation of one’s own actions. We would therefore expect that the internal representation of one’s own movements and associated interoceptive representations, which are essential for survival, would be more activated while viewing images of one’s own body in an unstable state (from the third person perspective), as compared to viewing the bodies of others\textsuperscript{26-30}. We further reasoned\textsuperscript{26-30} that the brain activity observed while viewing such images would closely approximate that which occurs in response to in-vivo body instability (e.g., slipping suddenly and almost falling down).

**Methodology based on self-recognition paradigm**

Thirteen right-handed healthy male participants (mean age = 24.7 ± 4.3 years) took part in the experiment. The stimuli were video clips of the participants’ own bodies as well as four other unfamiliar individuals, presented across three different conditions: Statically stable (SS), dynamically stable (DS), and dynamically unstable (DU). Each participant was instructed to stand and maintain their balance on three kinds of wooden balance boards: With two quadrangular pillars (SS), two round pillars (DS), and one round pillar (DU) (Fig. 1). In the DS condition, the board was moved horizontally at cycles of about 0.27 ± 0.03 Hz and with a range of about 10 cm. In the DU condition, the participant was instructed to keep the board horizontal as much as possible. Clips depicting the self were identified as such using a white mark positioned to the right above the image (Fig. 1). For the present purpose of using fMRI to identify brain activity associated with awareness of body instability, we defined “body instability”, or the unstable components of whole body movements, as the differential visual information based on the subtraction of DS (predictable and stable movements) from DU (unpredictable and unstable movements).

We contrasted brain activity during DU and DS conditions, separately, for self and other (Self DU vs. Self DS, Others DU vs. Others DS), to investigate the neural basis of body instability-related visual information processing, and these contrasts were also directly compared (Self [DU vs. DS] vs. Others [DU vs. DS]) to investigate self-specific neural processes related to body instability. We here defined “self-specific neural activity” related to body instability as follows: significant activation for the above contrast (Self [DU vs. DS] vs. Others [DU vs. DS]), and eigenvariates (averages) in the spherical ROI (radius, 5 mm) centered at each cluster showing significant positive activity in the above self contrast (DU vs. DS).

**Neural activity for processing one’s own body instability**

The right dorsal premotor cortex (PMd), parieto-insular vestibular cortex (PIVC)/temporo-parietal junction (TPJ), inferior parietal lobe (IPL), fusiform gyrus, putamen and caudate nucleus, left anterior supramarginal gyrus (aSMG), and the fusiform gyrus were significantly activated in the self-condition (Self DU vs. Self DS) (Fig. 2, Self).

In monkeys, the PIVC, a structure at the posterior end of the insula, constitutes the core region of the vestibular cortex, as this area contains many vestibular-driven neurons\textsuperscript{30-32}. The PIVC is also considered to be the core region of the vestibular cortex in humans\textsuperscript{31,33-35} and receives disynaptic inputs from the vestibular complex via the thalamus\textsuperscript{36,37}. PIVC activity during vestibular stimulation is stronger in the right hemisphere in right-handers\textsuperscript{38}, in accordance with our finding. In addition, right perisylvian

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**Fig. 1** Three kinds of wooden balance boards. The participant was instructed to stand and maintain his balance on two quadrangular pillars (statically stable) (left), two round pillars (dynamically stable) (middle), and the one round pillar (dynamically unstable) (right). A white circle was marked to the right above the self-clip.
areas, including the IPL, are also related to vestibular functioning in humans (caloric or galvanic) and the PIVC is connected with the pulvinar area, suggesting possible routes for visual inputs pertaining to body instability to the vestibular cortex. In addition, the right TPJ, which partially overlaps with the PIVC, receives somatosensory, visual, and vestibular inputs. This region plays a critical role in the encoding of spatial aspects of bodily self-consciousness and is activated by salient changes in sensory stimuli. Thus, activity in this region may be related to information processing of the spatial aspects of highly salient and potentially dangerous bodily movements.

There was also significant activation of the right PMd (corresponding to the lower extremities and trunk), caudate, putamen, and left aSMG. These brain regions may be involved in automatically and rapidly transforming information regarding one’s unstable movements from the visual allocentric space to the egocentric motor/body spaces, based on one’s own body-schema. A meta-analysis of the functional neuroimaging studies of action representations illustrates that extensive activity overlap exists between the motor-related brain areas during action observation, simulation, and execution. Moreover, the SMG is an important node in the network of fronto-parietal sensorimotor-related areas that represent limb movements. The left SMG is particularly active during a variety of tasks involving tools and spatiotemporal control of skilled actions, and plays a key role in representing memories for skilled praxis, suggesting that the left SMG underlies body-schema representation. In addition, the left aSMG changes rapidly for the optimization of responses to vestibular input during whole-body perturbations, suggesting that the body-schema is flexible and can adapt to novel environments.

A schematic model of processing one’s own body instability

Based on these considerations, the neural processing pertaining to one’s own body instability appears to consist mainly of the following three processes. First, there is a visual process for extracting dynamic body instability, in which body instability is extracted from visual representations of one’s own whole-body movements. Secondly, there is a motor/body process for space transformation (allocentric → egocentric), in which the instability components are interpreted as one’s own unstable bodily state based on one’s body schema. These two processes are associated with fusiform regions, the PMd, SMG, putamen, and caudate. Finally, there is a vestibular process in which the degree of body instability is estimated via the PIVC.

Neural activity for processing others’ body instability

The right EBA and left SPL were significantly activated in the Others DU vs. Others DS contrast (Fig. 2, Others). These areas appear to be involved in processing others’ body instability. The right EBA, which is activated strongly and selectively in response to static and dynamic images of human bodies and body parts, is
activated to a greater extent by allocentric than egocentric views\(^52\)-\(^54\), and responds more to impossible than possible movements\(^55\). This activity might be required for the visual analysis of others’ body instability, in agreement with previous findings that the recognition of others is related to visual processing, whereas recognition of self is more related to motor processes\(^19\) (Fig. 3). In addition, left SPL activity is thought to be critical in the visual analysis of others’ instability via the processing of specific body parts\(^56\).

Self-specific neural activity during body instability processing

Self-specific activity was found in the right rostral lateral prefrontal cortex (RLPFC), inferior frontal junction/ventral premotor cortex (IFJ/PMv), posterior insular cortex and parabrachial nucleus (PBN), as well as the left lingual, fusiform, and parahippocampal regions. Among these brain regions, the IFJ/PMv, posterior insula, and PBN appear to be the specific regions that underlie genuine body instability (Fig. 4), based on previous studies.

We expected that brain regions related to homeostatic processes might be involved in self-specific body processing, given that one’s sense of self is critical for survival. As expected, right PBN and posterior insula activation was observed during the processing of one’s own body instability. The communication between vestibular nuclei and the PBN is bidirectional, suggesting that the discharge of some vestibular nucleus neurons may represent contextual information regarding the level of danger indicated by incoming gravito-inertial information\(^57\). The PBN contains cells that respond to body rotation and position relative to gravity, and it appears to be an important node in a primary network that processes convergent vestibular, somatic, and visceral information to mediate avoidance conditioning, anxiety, conditioned fear responses, and various other affective responses, including panic associated with falling\(^57\). The response properties of PBN units are appropriate for a sensory signal to detect anomalies in head stability control, as a consequence of body postural control loss relative to gravity\(^58\). Accordingly, self-specific PBN activity during the processing of one’s own body instability might evoke such responses to dangerous departures from normal and stabilized movement trajectories. While the vestibular information for discriminating signals reflecting whole body trajectory changes may contribute to either postural control or adaptive cardiovascular (e.g., vestibule/sympathetic) response through descending PBN connections to the vestibular nuclei, medulla, and spinal cord\(^59\)-\(^60\), inertial guidance monitoring may provide interoceptive information to ascending pathways from the PBN ipsilaterally to the insula via the thalamus.

The insular cortex is organized in a hierarchical caudal–rostral direction, whereby primary sensory inputs projecting to the posterior insula, including somatosensory, vestibular and visceral inputs, are progressively elaborated and integrated across modalities in the middle insula\(^54\),\(^61\). The insula differentiates sympathetic and parasympathetic activity\(^62\),\(^63\), and electrical stimulation of the right insular cortex elevates diastolic blood pressure and heart rate while stimulation of the left insula decreases heart rate\(^64\),\(^65\). Sympathetic activity appears to be represented in the right hemisphere\(^62\),\(^65\), suggesting high sympathetic activity specific to one’s own body instability.

A meta-analysis shows that IFJ/PMv\(^66\) activity is associated with interpretation of potential threat-related stimuli\(^67\),\(^68\). In particular, perceiving fear during dynamic body expression induces right PMv activity\(^69\). Moreover, electrical stimulation of the dorsal polysensory area of the PMv evokes a specific set of defensive movements (avoiding, protecting, and withdrawing)\(^70\). The centering movement of the eyes that occurs during defensive reac-
Body instability is evoked by stimulation of the polysensory zone sites\(^1\). One major function of the polysensory neurons may be to monitor nearby potentially threatening objects and to coordinate complex movements to protect the body surface from those objects, implicating involvement of the right IFJ/PMv in motor preparations/simulation for such defensive reactions to an impending bodily crisis.

In addition, previous studies have suggested that a defining function of the rostrolateral prefrontal cortex (RLPFC) is meta-cognitive processing\(^2\), or the process of reflecting upon one’s own mental contents\(^3-^6\). In the present study, our participants were supine in the MRI scanner and viewed video footage of themselves and others making potentially unstable and dangerous movements. Metacognitive processing might be required for processing one’s own movements but not those of others.

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**Fig. 4** Self-specific brain activity in the DU vs. DS contrast. PMv/IFJ, pINS, and PBN were significantly activated for the Self (DU vs. DS) vs. Others (DU vs. DS) contrast. PMv: ventral premotor area, IFJ: inferior frontal junction, PBN: parabrachial nucleus.

**Fig. 5** The PBN-centered neural model in response to crisis of whole body balance. Sensory information across modalities such as vestibular and visceral are conveyed to the PBN, which connects bi-directionally with the posterior insula and amygdala. The amygdala processes emotional aspects of the crisis, and the insula integrates various sensory and interoceptive information. Inferior parietal regions including the PIVC process degree of the crisis, and the PMv/IFJ generates the necessary defensive motor response. PMv: ventral premotor area, IFJ: inferior frontal junction, PBN: parabrachial nucleus, PIVC: parieto-insular vestibular cortex.
Additionally, the RLPFC is involved in motor learning, such that significant gray matter volume increases and fractional anisotropy (FA) decreases were observed in the RLPFC following only two practice sessions of a complex whole-body balancing task. Based on these considerations, the self-specific neural processing of body instability consists of at least three component processes: 1) a vestibular/interoceptive process related to detection of vestibular anomalies and to sympathetic activity as a form of alarm response (the right PBN and posterior insula), 2) an automatic motor-response preparation process (right IFJ/PMv), in which the necessary motor responses are automatically prepared/simulated in the brain to protect one’s body, and 3) a meta-cognitive process (right RLPFC) for self-recognition from the 3rd person perspective view.

Self-recognition recruits the genuine brain crisis-related activity

Among these components and corresponding brain regions, the right PBN, posterior insula, and IFJ/PMv are thought to be activated during the genuine experience of an unstable bodily state, together with the right PIVC, which is involved in body instability estimation (Fig. 5). In addition, all of the neural structures showed remarkable right dominance at both the cortical (PIVC, IFJ/PMv, and posterior insula) and brainstem (PBN) levels, the latter being directly connected to the vestibular nerve and therefore comprising a very primitive neural structure. This right dominance may be based on lateralization of homeostatic brain structures and functions, which has been evolutionarily driven by a preexisting behavioral and autonomic asymmetry that is present in all vertebrates.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this article.

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References


655-666.
71) Fujii N, Mushiake H and Tanji J. 1998. An oculomotor repre-
sentation area within the ventral premotor cortex. Proc Natl Acad Sci USA 95: 12034-12037.