SVOA Neurology

ISSN: 2753-9180

ScienceVolks Open Access

Mini-Review

Sense of Agency in Functional Movement Disorders: Insights and Perspectives

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Abstract

Functional movement disorders (FMD) are movement abnormalities that are distractible, inconsistent over time, and incongruent with typical features of movement disorders. The sense of agency (SoA) is the feeling of controlling one's own motor actions and, through them, the course of external events. Impaired self-agency is considered a key factor in the pathophysiology of FMD. While several theoretical models have been proposed to explain the SoA, the active inference model offers a comprehensive framework that integrates both sensorimotor and cognitive processes. Evidence from neuroimaging studies in FMD shows functional abnormalities in the brain regions associated with SoA, especially the right temporoparietal junction (TPJ) and supplementary motor area (SMA). Experimental paradigms like intentional binding and sensory attenuation have revealed a loss of agency in FMD. This review explores the theoretical models and current evidence regarding SoA impairment in FMD.

Keywords: *Sense of Agency, Functional Movement Disorder.*

Introduction

Functional movement disorders (FMD) are movement abnormalities that are distractable, inconsistent over time, and incongruent with typical features of movement disorders. [1][2]They can present as various phenotypes, including tremor, dystonia, myoclonus, gait disorders, and parkinsonism, and are very common in neurology practice. [3][4][5]

The sense of agency (SoA) is the feeling of controlling one's own motor actions and, through them, the course of external events. [6]Impaired self-agency is considered a key factor in the pathophysiology of several psychiatric and neurological conditions including schizophrenia, Parkinson's disease, corticobasal syndrome, Tourette syndrome, and FMD. [7]

The SoA spans over both neurological and psychological aspects of one's existence and daily behavior. In psychiatry, the SoA is often described in terms of internal and external locus of control. A higher sense of self-agency, referred to as internal locus of control, describes a stronger connection between internal self-agency and environmental outcomes. In contrast, a lower sense of self-agency, also known as an external locus of control, refers to a perception where outcomes are viewed as unrelated to one's own actions. Self-agency has also been linked to behavioral disturbances. [8] Higher self-agency is associated with resilience to stress, goal-directed behaviors, and overall well-being. [9][10][11] Lower self -agency is associated with negative emotionality and an increased risk of apathy and anhedonia. [12][13]

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https://doi.org/10.58624/SVOANE.2025.06.007

Received: January 12, 2025

Published: February 18, 2025

Citation: Murgai A, Patel SV, Iskhakova S. Sense of Agency in Functional Movement Disorders: Insights and Perspectives. *SVOA Neurology 2025,* 6:1, 33-38. doi: 10.58624/SVOANE.2025.06.007

The neural network underlying SA is complex and primarily distributed over the right hemisphere of the brain. [14] Neuroimaging studies have consistently identified the right inferior parietal lobe (IPL) as a key region responsible for generating the SoA. [15][16][17] Evidence from various experimental studies suggests that the SoA is impaired in individuals with FMD. This review explores the theoretical models and current evidence regarding SoA impairment in FMD.

Sense of Agency Models

The comparator model (Fig 1) was initially developed to explain sensorimotor control mechanisms and was later adapted to account for the SoA. [18]This model relies on predicting the sensory consequences of actions based on the original motor commands and comparing them to the actual sensory feedback. No mismatch between the predicted sensory consequences and the actual sensory feedback generates a sense of agency or feeling of being in control of one's action. If the sensory feedback perfectly matches the predictions, the prediction error is zero, confirming the internal predictive model and generating a sense of agency. [6]

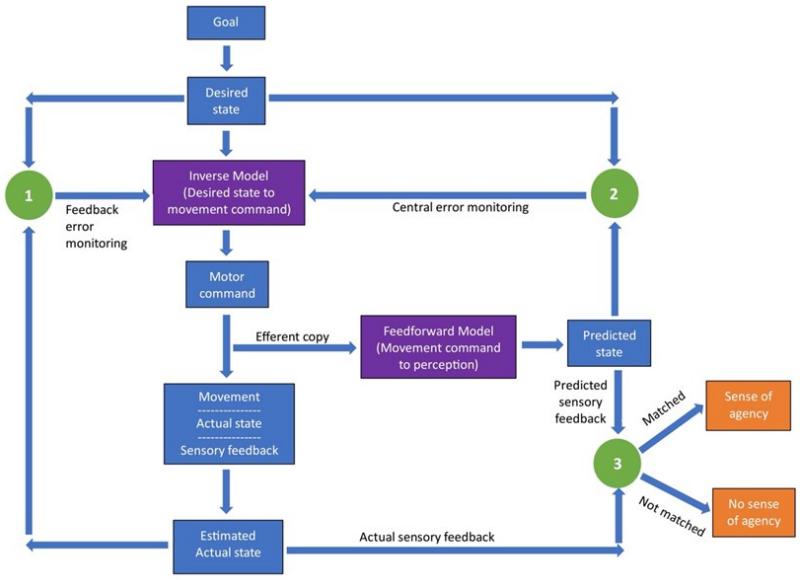

Figure 1: *Comparator model for motor control and sense of agency (Adapted from Frith et al., 2000; Synofzik et al., 2006). [18][19] An inverse model generates the motor command required to achieve an action based on the desired goal. The forward model uses an efference copy of the motor command to predict the sensory consequences of the action. After a motor command is executed, the system compares the estimated actual state to the desired state within the feedback control loop. This comparison calculates a motor error, which is then used to adjust the motor command and improve system functioning (Comparator 1). Based on a given motor command, the system predicts the outcome of an individual's behavior (predicted state). These predictions are used for feed-forward motor control, enabling central error monitoring of the movement without relying on sensory feedback (Comparator 2). The sense of agency is generated when the actual sensory feedback matches the predicted sensory outcome of the motor command. (Comparator 3)*

The comparator model alone is insufficient to explain the higher-order processes involved in the judgment of agency. A modified framework suggests that prediction errors must be transmitted to the higher-order associative cortex, where they are integrated with the contextual knowledge and beliefs to generate the judgment of agency. [19] This highlights that the sense of agency is achieved through multistep processes, extending from lower-level sensorimotor to higher-level cognitive functions. [17]

A more recent framework for understanding the sense of agency is the active inference model. It presents a more comprehensive framework for understanding SoA, incorporating both sensorimotor and cognitive processes. This model proposes that the brain minimizes 'free energy', a measure of uncertainty, by continuously predicting and adapting to its environment.

The brain constantly generates predictions about the world and reduces errors between these predictions and sensory feedback. The active inference model proposes that the brain is not just a passive recipient of sensory information but works actively to minimize uncertainty through its actions. Through actions, it minimizes prediction errors and gathers evidence to refine its internal model. [20]

A key component of this model is the human-environment interaction, which can be categorized into external process (s), representing the environmental state; observable process (o), representing sensory feedback perceived by the agent; and autonomous process (a), comprising actions generated by the agent. The active inference model is defined by its prediction and preference models. The prediction model P(s,o|a) represents the joint probability of the environmental state (s) and the sensory feedback (o) given a specific action (a), capturing how the brain predicts the consequences of voluntary actions. The preference model P(s,o) reflects the agent's prior goals or expectations, representing the joint probability of the desired environmental state (s) and the sensory feedback (o). It serves as a normative framework to evaluate how well the predicted outcome aligns with the agent's goal. It is a reference point or a standard that the agent considers desirable or optimal. The prediction model and the preference model interact by aligning predicted outcomes with the agent's goals, helping guide the actions toward achieving desired outcomes. [21]

In the comparative model, the sense of agency arises from comparing sensory predictions with the sensory feedback. When a match occurs, the sense of agency is strong. This process is believed to be binary as the predictions either match or they don't. [6][22]The active inference model goes beyond these binary comparisons by using the Bayesian principle and error reduction. Active inference allows for a graded sense of agency rather than a binary attribution, and it emerges dynamically by minimizing uncertainty over time. [23] In active inference framework, the brain continuously refines its internal model by minimizing the difference between predicted and actual sensory inputs.

Components and Measurement of SoA

The sense of agency consists of two components. The first component, known as an implicit agency or the "feeling of agency," involves a low-level, non-conceptual, implicit sense of control over actions without a relationship to the conscious thoughts. [19][6] It is the vague sense of control of the voluntary actions experienced even in the absence of conscious attention to those actions. The second component, known as the "judgment of agency," involves the conscious awareness of being the creator of one's actions. [19] This explicit judgment requires individuals to attribute their sensory experiences to their actions. It can be shaped by cognitive biases, particularly in relation to positive outcomes. Both the feeling of agency and the judgment of agency are distinct processes that together contribute to the overall sense of agency.

Assessing the judgment of agency can be done simply by asking a subject if they believe they were the author of a specific action. In contrast, the measure of the implicit feeling of agency requires an experimental setup. The classical method to measure the implicit component of the sense of agency is by using intentional binding tasks, which focus on the perception of time. Intentional binding is the compression of the perceived time interval between an action and its outcome. It is the phenomenon where a voluntary action (e.g., pressing a button) and its sensory outcome (e.g., a tone) are perceived as occurring closer together in time than they actually occur. [6]

Sensory attenuation is another implicit measure of self-agency, classically measured using force-matching tasks. It refers to the fact that the sensory consequences of our actions are perceived differently from identical sensory input when it is externally generated. For example, a self-produced tactile stimulus is perceived as less ticklish than the same stimulus generated externally. In a sensory attenuation force-matching experiment, a target force is applied to the subject's finger by a torque motor. Subjects are then asked to match this reference force either directly by pressing with a finger of their other hand or indirectly by using a joystick controlling the torque motor. Healthy subjects consistently exert greater force than necessary during direct pressing compared to using a joystick controlling the torque motor. This excess force reflects sensory attenuation or the diminished perception of sensory feedback during self-generated movements. [24] [25]

Sense of Agency in FMD: Current Evidence

Experimental evidence has provided some, although not extensive insight into SoA experienced by patients with FMD. Patients with FMD show reduced functional connectivity between the right temporoparietal junction (TPJ), right sensorimotor cortex, cerebellar vermis, bilateral supplementary motor area, and right insula. Reduced functional connectivity between the right TPJ and the sensorimotor cortex suggests that impaired motor planning and altered sensory feedback contribute to a weakened sense of self-agency. [16]

In patients with functional tremor, decreased activity in the right TPJ and reduced connectivity with the sensorimotor cortex have been observed. This disruption likely reflects an impairment in sensory prediction processes, leading to the perception that movements are not self-generated. [26]

The supplementary motor area (SMA) and pre-SMA play key roles in voluntary, self-initiated actions. Activation of the left SMA, for example, triggers voluntary movements of the right hand. A study in healthy individuals showed a correlation between SMA activity and the subjective experience of linking an action to its consequence, concluding that SMA activation is involved in agency-related intentional binding. [27] Another functional neuroimaging study in FMD patients found selective dysfunction involving the right dorsolateral prefrontal cortex and pre-supplementary motor area. [28]

Intentional binding, a measure of implicit sense of agency, has been shown to be altered in individuals with FMD. An experiment examining intentional binding in patients with FMD revealed decreased action-effect binding during normal voluntary movements compared to healthy controls, suggesting a diminished sense of agency or a greater experience of lacking control in individuals with FMD. [29] In another study, subjects with functional tremor and healthy controls were asked to identify the timing of a self-paced button press relative to a clock displayed on a computer screen. In separate trials, they were asked to evaluate the timing of their internal feeling of intention to move. Functional tremor subjects experienced the intention to move significantly later and, therefore, closer to the movement itself. They were also delayed relative to controls in their judgment of the time of their action. The interval between the perceived time of intention and the perceived time of action was highly significant in the control subjects and much smaller and nonsignificant in the functional tremor subjects. This study provided evidence for an impaired time perception and sense of volition prior to movement in functional tremor patients. [30]

Some studies have shown a normal sense of agency in functional movement disorders when assessed using explicit measures. Explicit measures of agency, assessed through a questionnaire during an action-recognition task, were preserved in individuals with FMD.[31] Priming paradigms, often used to explore how exposure to stimuli influences subsequent actions and decisions, provide further insight. In subliminal priming, stimuli are presented for a very brief period of time that they remain below the threshold of conscious awareness, whereas supraliminal priming uses stimuli that are consciously perceived. Subliminal priming is believed to implicitly influence the voluntary motor pathway, whereas supraliminal priming does it explicitly. A study using these techniques demonstrated that individuals with FMD exhibited intact motor responses and a preserved sense of agency under both subliminal and supraliminal priming conditions. [32]

Sensory attenuation, a phenomenon where the intensity of sensation caused by self-generated movement is reduced, is closely related to the sense of agency. [33] A loss of sensory attenuation has been suggested as an indicator of diminished SoA for self-generated movement. [33] In an experimental setup for measuring sensory attenuation, participants were required to match forces either by pressing directly on their own finger or by operating a robot that applied force on their finger. Compared to individuals with FMD, healthy participants consistently overestimated the required force when pressing directly on their own finger compared to when using the robot. This study observed a loss of sensory attenuation in people with FMD. The loss of sensory attenuation has been associated with a diminished SoA, which could explain why individuals with FMD perceive their abnormal movements as involuntary. [25] Sensory attenuation can be probed in a simpler way by studying the suppression of sensory evoked potentials (SEP) at the onset of self-generated movements. Patients with FMD show reduced SEP attenuation at the onset of movement compared to healthy controls, highlighting their reduced sensory attenuation and diminished sense of agency. [34]

Conclusions

The sense of agency plays an important role in our ability to perceive control over our actions and their consequences, and its impairment is central to the pathophysiology of FMD. The active inference model suggests that the brain actively explores and interacts with the environment to update its internal model. It offers a comprehensive framework for understanding SoA by integrating both sensorimotor and cognitive processes. Evidence from neuroimaging studies in FMD shows functional abnormalities in the brain regions associated with SoA, especially the right TPJ, dorsolateral prefrontal cortex, and supplementary motor area. Experimental paradigms exploring intentional binding, and sensory attenuation have revealed a loss of agency in FMD. Understanding these mechanisms not only sheds light on the understanding of FMD but may also help in developing innovative diagnostic tools and therapeutic interventions.

Ethical Compliance Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this work is consistent with those guidelines.

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