

From Prediction to Integration: Subprocesses of Action Emulation and Their Neurophysiological Basis

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The ability to move while constantly integrating sensory information from the environment is a fundamental aspect of human life. Despite the apparent simplicity of this process, sensorimotor control requires dealing with uncertainty, noise and varying predictability just within milliseconds. These processes engage broadly distributed cortical networks and complex oscillatory dynamics. Similar patterns of brain activity during action execution and imagery suggest an abstract neural representation of movement in the brain. The Emulation Theory (Grush, 2004) provides a theoretical framework for the common basis of imagined, predicted and executed action. This dissertation investigated the subprocesses of action emulation and sensorimotor integration and their neurophysiological underpinnings. Four studies were conducted to extend our understanding of how the brain achieves successful sensorimotor integration, particularly under the influence of varying uncertainty and predictability. A continuous pursuit-tracking paradigm with different variants was employed in conjunction with electroencephalographic recordings to answer four different research questions.

In the first study, a new paradigm and behavioral metric to assess continuous sensorimotor integration were developed. The new behavioral metric provided insights into the mechanistic underpinnings of sensorimotor integration by distinguishing feedforward- and feedback-driven movements. The results of the first study showed that feedforward and feedback processes jointly contribute to successful sensorimotor control, with sensory feedback directly informing the motor plan.

The second study investigated the neurophysiological dynamics supporting continuous sensorimotor integration. Two consecutive pursuit-tracking paradigms were implemented, combining EEG and behavioral measures. The results showed that there is a differential weighting of feedforward and feedback information depending on uncertainty in the environment. This dynamic weighting is supported by a neural cascade involving early sensorimotor calibrations via alpha-band (ABA), beta-band (BBA) and theta-band activity (TBA), with TBA also coding a need for cognitive control later on. Feedforward and feedback inputs are dynamically weighted in a so-called reference variable and jointly inform the resulting motor plan.

The third study aimed to reveal oscillatory activity patterns and neural sources underlying subprocesses of action emulation during increased uncertainty. Three variants of the pursuit-

tracking paradigm were implemented, systematically varying uncertainty related to the action goal or sensory feedback while recording EEG data. The results corroborated findings that the dynamic weighting of feedforward and feedback information is shifted under increased uncertainty. The different processing during increased uncertainty is related to changes in a ventral-path cascade of TBA and BBA that potentially compensates for the effect of uncertainty-related input.

In the fourth study, the directed neural network dynamics in TBA-related networks supporting sensorimotor integration under varying predictability were investigated. To understand age-related dynamics, an adult and an adolescent sample were recruited to perform a pursuit-tracking task with different degrees of predictability. The results revealed that input from the action goal is differentially weighted according to predictability, with the cingulate cortex regulating a ventral-path cascade of TBA in adults, potentially leading to enhanced performance compared to adolescents.

Based on the empirical results, a new model of action emulation was developed, including the contributions of different oscillatory activity patterns. The new model postulates that emulated feedback is of particular relevance during the formation of the initial motor plan, and is related to ABA. During the dynamic updating of motor plans, complex patterns of BBA and TBA differentially weight input from action goal and sensory feedback. This weighting process is likely developed by different rhythms of information sampling, related to different oscillatory modes in the underlying brain activity. Future research should focus on understanding the function underlying the weighting process, for instance by systematically varying the feedforward information about the action goal and investigating potential (non-)linear scaling with oscillatory brain activity. By employing sophisticated modelling approaches such as dynamic time warping and sequential sampling models, the understanding of underlying mechanisms could be further refined and might provide a basis for applications in clinical contexts or robotic technologies.