Volition under uncertainty

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Introduction

Voluntary actions are distinct among human behaviours in several ways. They involve both an ordered series of neural events in the premotor areas of the brain [1-3], and also a characteristic conscious experience of controlling one's actions, i.e., the "sense of agency" [4].
Voluntary actions are normally guided by a combination of **endogenous** cues, e.g., external stimuli and information, and **exogenous** factors, e.g., prior beliefs, desires, and "intentions" [5, 6]. Contrary to the so-called "stimulus-driven actions", the endogenous and endogenous factors associated with voluntary actions are rarely deterministic. Instead, they can be characterized by a variable degree of **uncertainty**. However, how the brain processes this uncertainty and combines exogenous and endogenous stimuli to generate the appropriate voluntary action to accomplish the goal is still unknown.
In this project, a set of experiments explored whether the degree of endogenous and endogenous uncertainty about the upcoming movement modulates the neural activity during motor preparation of voluntary actions, as well as the behavioural experience of agency.

Methods

In two experiments, participants performed a temporal reinforcement learning task that allows them to learn, through feedback, the best time to act [7]. Our cover story treated participants as farmers, planting a seed into the ground at the beginning of each trial. Their task was to wait until the fruit was ready, and then press a key to harvest at the exact right time. Participants received feedback on their performance, depending on whether they harvested the fruit before or after it was ready, or at the exact right time. Through their action feedback, they learned the optimal waiting time, progressively reducing the **endogenous uncertainty** about the appropriate action to accomplish the task. Crucially, the feedback scheme followed a probability distribution. In one condition (narrow bandwidth) the probability of receiving positive feedback was lower but the feedback was more informative and precise (**lower exogenous uncertainty**). In another condition (large bandwidth), getting positive feedback was easier but the feedback was less precise (**greater exogenous uncertainty**).
Exp1 (N=25) examined possible modulations of endogenous and endogenous uncertainty on the EEG *Readiness Potential* (RP), i.e., a gradual increase in negativity that ramps up over the second or so prior to voluntary action.
Exp2 (N=26) measured the *intentional binding effect*, an implicit marker of the sense of agency. In this experimenter, the participant's voluntary action was followed, after a variable delay, by an auditory tone. Participants estimated the interval between action and tone. The intentional binding effect corresponds to a perceived compression between the time of the voluntary action and its sensory consequence, relative to a control condition without voluntary actions [8].

Results

Our results from the exp1 showed that the RP increased with learning, i.e., the RP slope increased as endogenous uncertainty about the correct time to act decreased. However, this RP increase was evident only in the condition of narrow bandwidth (low exogenous uncertainty). When the bandwidth was large (high exogenous uncertainty), there was no difference in the RP slope between the earlier and later stages of learning. Computationally, our data suggested that the RP decrease with learning may correspond to a process of **faster accumulation** within a leaky stochastic accumulator model.

Conversely, the results from the exp2 showed that learning the correct time to act (less endogenous uncertainty) reduced the intentional binding effect between actions and outcomes. The reduction was greater when the bandwidth was larger (high exogenous uncertainty) than narrow (low exogenous uncertainty).

Discussion

Our results showed that uncertainty influences a classical neural precursor of voluntary action: RP slope increased as the endogenous uncertainty decreased. We further showed that RP increase depends on the amount of the exogenous uncertainty: when the external environment is more certain and provides more informative feedback to learn, the RP increases with learning. Conversely, when the external environment is more uncertain and less effective in guiding the behaviour, there is no difference in the RPs depending on the precision of the internal model of the action. In that sense, the neurocognitive processes underlying voluntary action seem to be upregulated when we know what we want to do, and when we additionally receive reliable feedback cues from the environment about what we should do.

Conversely, we found evidence that sense of agency reduced with learning. We hypothesise that this reduction might be linked to a less salient representation of the self-generated stimulus. Once the internal model of the world is learned and stable, feedback might be less important to modify the behaviour. This salience reduction might rest upon a sensory attenuation mechanism [9] - which will be the subject of our future investigations.

References

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