The role of the Cerebellum in Social Action Sequences

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Introduction

In a recent meta-analysis, Van Overwalle et al. (2014) demonstrated that the posterior cerebellum is implicated in "mind" reading or understanding others' beliefs and traits.

What is the cerebellum doing for mind reading? At a general level, the primary function of the cerebellum is to support sequence learning of movement by internal models which automate motor execution after practice. During evolution, a more advanced function developed which allowed the cerebellum to construct internal models of purely mental processes in which event sequences play a role, without overt movements (Ito, 2008; Leggio et al., 2011; Pisotta & Molinari, 2014). Here we test whether these sequential processes also subserve social mind reading using a variety of novel tasks involving sequences of social actions.

Action Sequencing Tasks

In various tasks, participants had to…

1. **Picture Sequencing**: reconstruct the chronological order of event sequences in a cartoon-like story, some of which involve *true* and *false beliefs* (Figure 1; extended from Langdon & Coltheart, 1999).
2. **Story Sequencing**: same with verbal 4-sentence material.
3. **Trait-implying Sentence Ordering:** learn the exact order of unrelated actions, except that they all implied a *trait* of a single person (Pu et al., 2019).
4. **Serial Belief Reaction Time Task:** indicate how many flowers were given to a male or female smurf while he or she was looking towards it or not – and as he or she saw and believed it. Unbeknownst to the participants, there was a fixed sequence in the location of the flowers, the smurf to whom the flower was given, and most importantly, the smurf's orientation towards the screen (*true belief*) or away from the screen (*false belief*, in this case the correct answer is the prior trial when the smurf was looking to the screen; Figure 2; Ma et al., 2019).

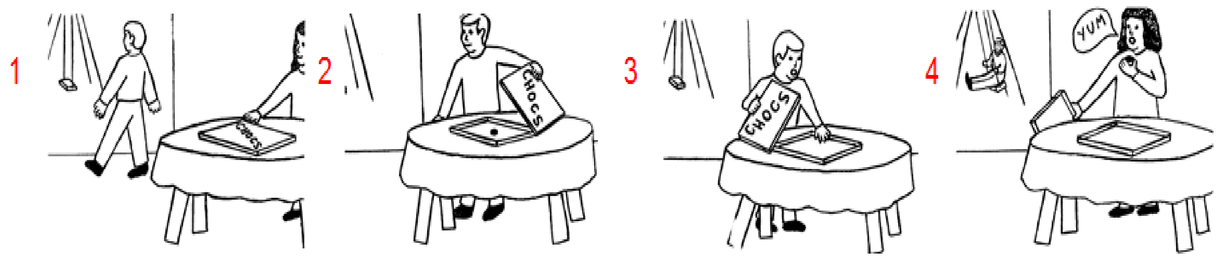


Figure 1: An example of a false belief sequence (correct order is 2 – 1 – 4 – 3).

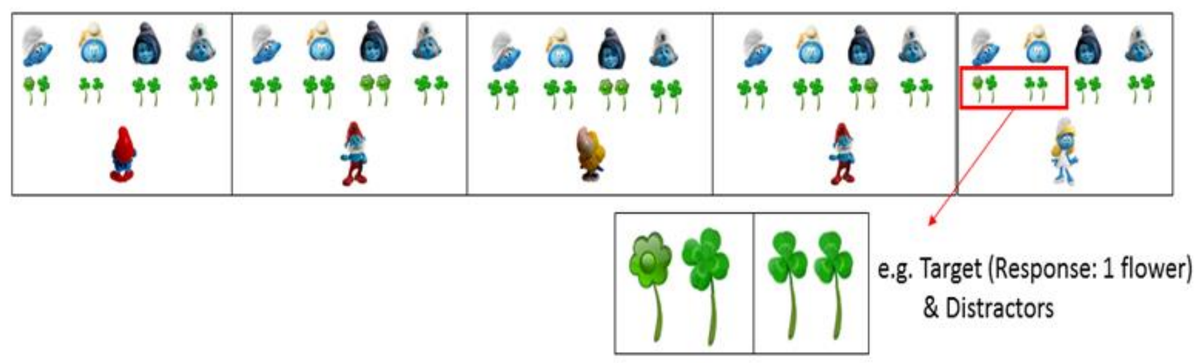


Figure 2: The serial belief reaction time task: on each trial, participants report the amount of green flowers as seen by the smurf when turned to the screen (*true belief*). When turned away from the screen (*false belief*) the correct answer is the prior trial when the smurf was looking at the screen. Without being informed, there was a fixed sequence of flowers' locations, the smurf who received the flowers, and true and false beliefs. The amount of flowers was completely random, hence making the response unpredictable from trail to trial, and dissociating belief sequence learning from motor response learning.

Results of Studies (see Figure 3)

Study 1 - Picture Sequencing - patients (Van Overwalle et al., 2019)
Degenerative cerebellar patients (n=8) in comparison with matched healthy controls (n=8), revealed significant impairments, especially for the generation of a correct script order during *false* belief events, and not for routine social and mechanical scripts.

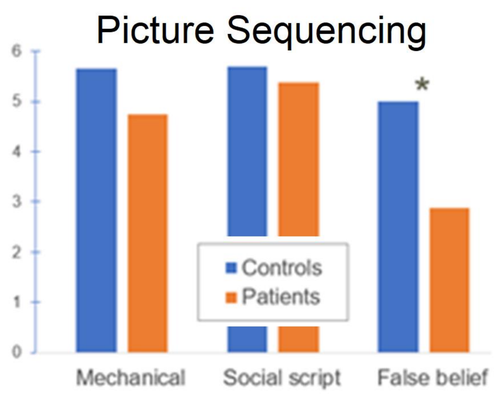
Study 2 - Picture & Story Sequencing – fMRI (Heleven et al., 2019)
True and false belief pictures and verbal stories showed increased activation in the posterior cerebellum in comparison with routine mechanical and social scripts.

Study 3 - Trait-implying Sentence Ordering – fMRI (Pu et al., 2020)
Learning the order of sentences implying the *trait* of a person increased activation in the posterior cerebellum in comparison with sentences implying the feature of a non-social object.

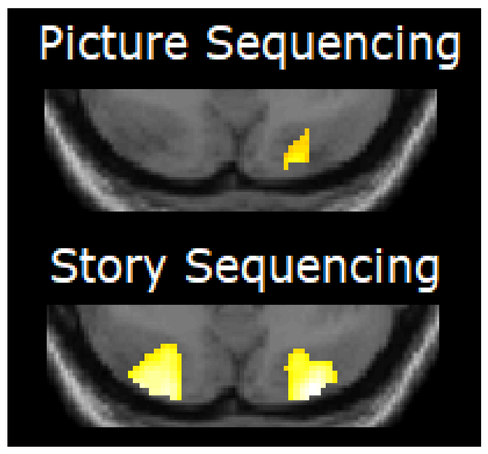
Study 4 - Serial Belief Reaction Time Task – behavioral & fMRI
Behavioral study indicated that participants accurately inferred true and false beliefs, and implicitly learned the critical *true-false belief* order (Ma et al., 2020).
The fMRI study revealed stronger posterior cerebellar activation during initial learning and random trials compared to subsequent test trials with the standard fixed *true-false belief* sequence (Ma et al., in preparation)

Figure 3:

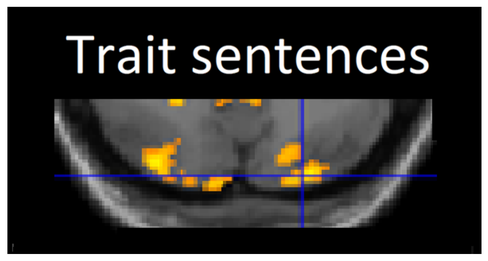
Study 1 - Comparison of 8 degenerative cerebellar patients with 8 healthy controls on the Picture Sequencing task. * $p < .002$ (one-sided t-test). (Van Overwalle et al., 2019)



Study 2 - Transverse view of activation in the posterior cerebellum in the Picture and Story Sequencing tasks for true + false belief > mechanical conditions (z=-36; FWE-corrected $p < .05$). (Heleven et al., 2019)



Study 3 - Activation in posterior cerebellum while learning the order of social sentences implying the trait of a person > non-social sentences involving the feature of an object (z=-36; uncorrected $p < .001$). (Pu et al., 2020)



Study 4 - Activation in posterior cerebellum while implicitly learning the order of fixed true – false trials during initial learning > later testing (z=-34; uncorrected $p < .001$). (Ma et al., in preparation)

Conclusion

The present studies confirm that the posterior cerebellum is involved in sequencing of actions, which is a prerequisite for understanding false and true beliefs held by others. This highlights the neglected contribution of adequate story understanding and sequencing in efficient social cognition and interaction.

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