HOW DOES THE CEREBELLUM CONTRIBUTE TO LANGUAGE LEARNING? A LINGUISTIC EXTENSION OF THE INTERNAL MODEL ACCOUNT

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INTRODUCTION

The cerebellum is hypothesized to encode internal models for cognition, which are refined through error-based learning to help the brain perform tasks precisely and automatically (Ito, 2008).

This research aims to apply the internal model framework of cerebellar function to **explicit** artificial language learning using **functional magnetic resonance imaging (fMRI)**, with a specific focus on the effects of associativity/grammaticality and feedback.

We predicted:

- There would be co-activation and functional connectivity (FC) between bilateral Crus I/II and cerebrum ROIs.
- Incorrect word-meaning associations/ ungrammatical sentences and negative feedback would elicit increased co-activation but decreased FC.

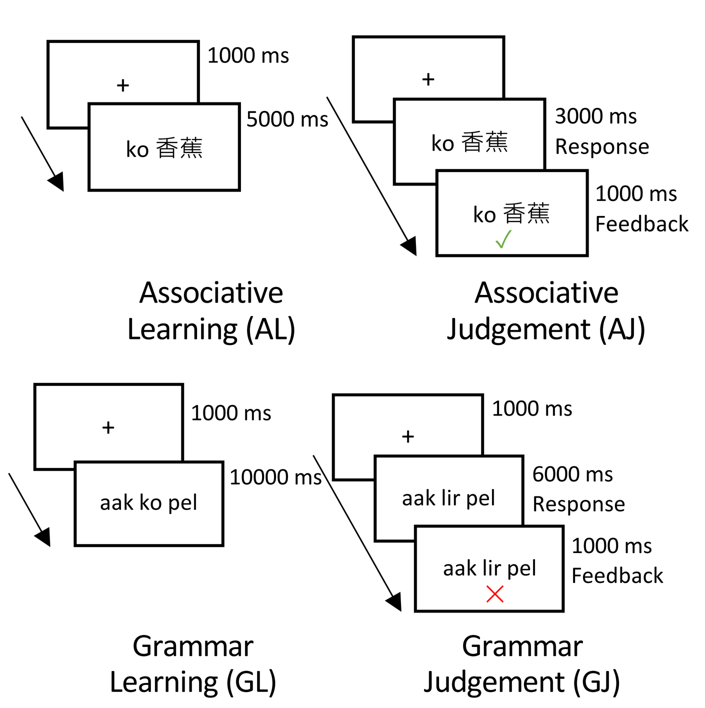
TASK

Twenty native Cantonese speakers from Hong Kong (aged 18-27, 11 females, all right-handed) were recruited. They completed the following tasks in four weeks:

Week 1: Behavior test

- Cognitive abilities: interference control (Stroop), working memory (digit and reading span), intelligence (Raven's SPM), cognitive flexibility (WCST)
- Language abilities: proficiency (HKDSE), experience (LHQ), analytical ability (LLAMA_B/F)

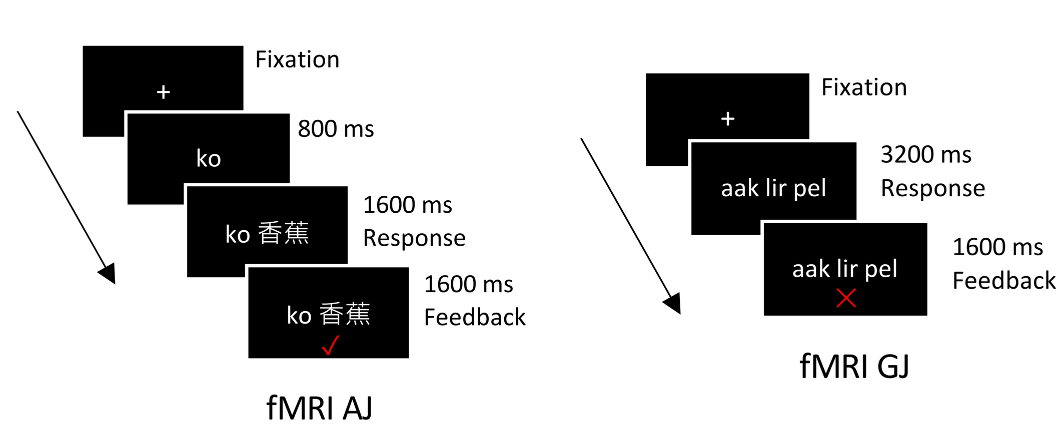
Week 2: Artificial language learning



Week 3-4: Training (3 sessions)

Exercise (matching, translation, correction) + AL + AJ + GL +GJ

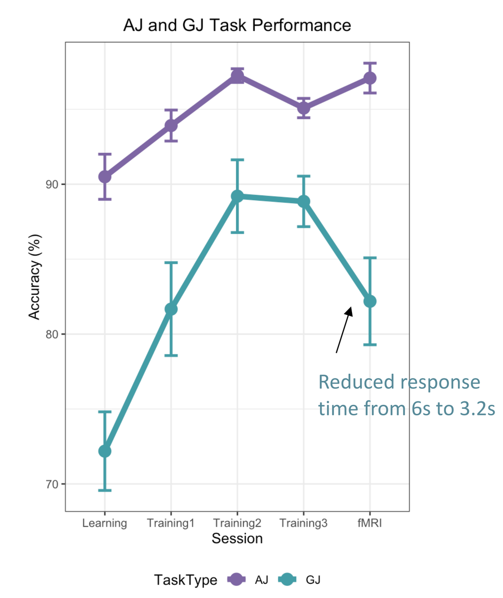
Week 4: fMRI (+ T1 and T2)



AJ: 6 blocks, 10 trials for each block (2 filler) ~10 mins
GJ: 16 blocks, 7 trials for each block (1 filler) ~22 mins
Rest: 24s after each block

BEHAVIORAL RESULTS

1 Acquisition: Participants showed overall improvement in accuracy across sessions and proficiency in both AJ (ACC = 94.8%, RT = 1092 ms) and GJ tasks (ACC = 82.8%, RT = 3145 ms).



2 Individual difference: stepwise regression

Associative Judgement

Cognitive abilities (AIC= -91.80)
($F(2,17) = 3.79$, $p = .044$, Adjusted $R^2 = .227$)

Interference ($t(17) = 1.685$, $p = .110$)
Reading span ($t(17) = 2.114$, $p = .050$)

Language abilities (AIC=-88.02) ★
($F(4,15) = 4.25$, $p = .017$, Adjusted $R^2 = .406$)

LLAMA_B score ($t = 2.480$, $p = .030$)
English DSE grade ($t(15) = 2.530$, $p = .023$)
L1 dominance ($t(15) = 2.129$, $p = .050$)
Multilingual diversity ($t(15) = 2.649$, $p = .018$)

Grammar Judgment

Cognitive abilities (AIC=-4784) ★
($F(3,16) = 12.1$, $p < .001$, Adjusted $R^2 = .637$)

Digit span ($t(16) = 2.172$, $p = .045$)
Reading span ($t(16) = 2.119$, $p = .050$)
WCST non-perseverative error ($t(16) = -4.34$, $p < .001$)

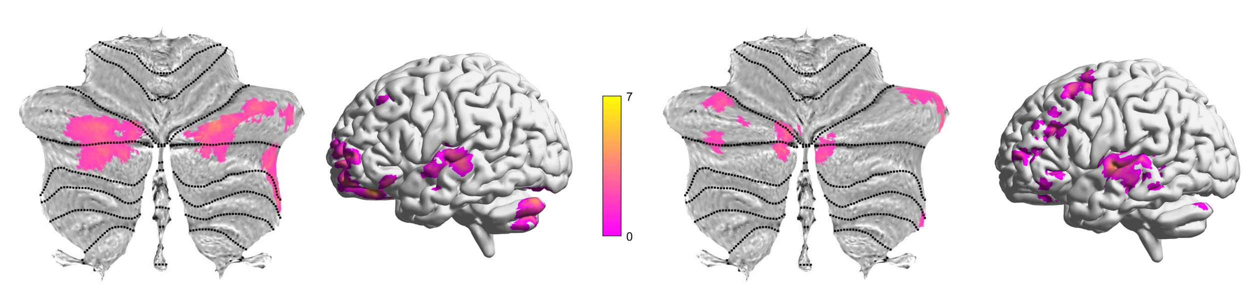
Language abilities (AIC=-39.37)
($F(3,16) = 6.076$, $p = .006$, Adjusted $R^2 = .445$)

Chinese DSE grade ($t(16) = 3.941$, $p = .001$)
L1 dominance ($t(16) = -1.365$, $p = .191$)
Multilingual diversity ($t(16) = 1.403$, $p = .180$)

CO-ACTIVATION

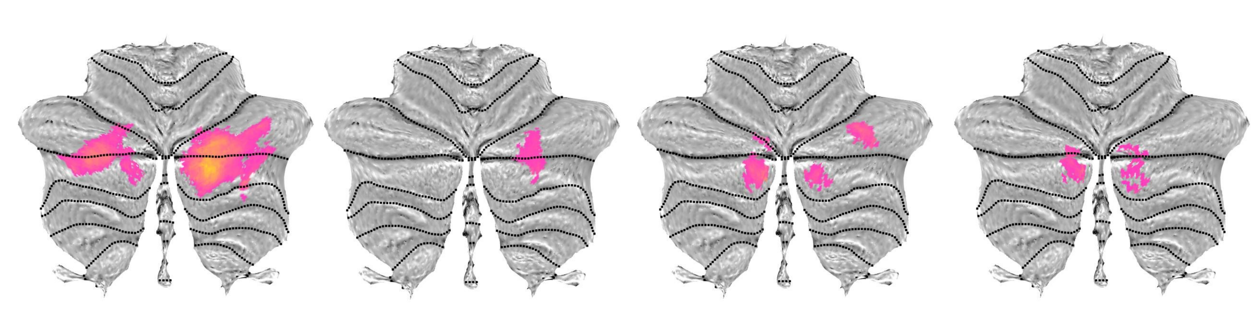
ROIs: Prefrontal cortex: IFG, MFG, SFG; Temporal cortex: STG, MTG; Parietal cortex: AG; Subcortical region: BG, Tha, HP; Cerebellum: Crus I/II

3 AJ: Activations were observed in bilateral Crus I/II, left STG, left IFG, and left BG during judgment. Correct word-meaning pairs elicited increased activations in bilateral Crus I/II, left STG, right BG, right SFG, and left MFG.

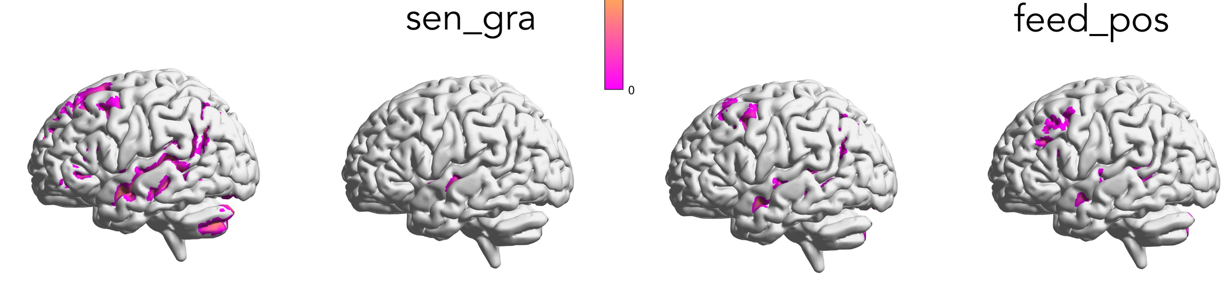


word > rest   word_cor > word_inc

4 GJ: Activations were observed in bilateral Crus I/II, left MTG, and left MFG during judgment and feedback. Ungrammatical sentences elicited increased activation in right Crus I/II and left STG. Negative feedback elicited increased activations in bilateral Crus I/II, bilateral MFG, and left MTG.



sentence > rest   sen_ung > sen_gra   feedback > rest   feed_neg > feed_pos



*We did not analyze the effects of positive and negative feedback for AJ due to insufficient data. Uncorrected $p < .05$ at voxel level, FDR-corrected $p < .05$ at cluster level .

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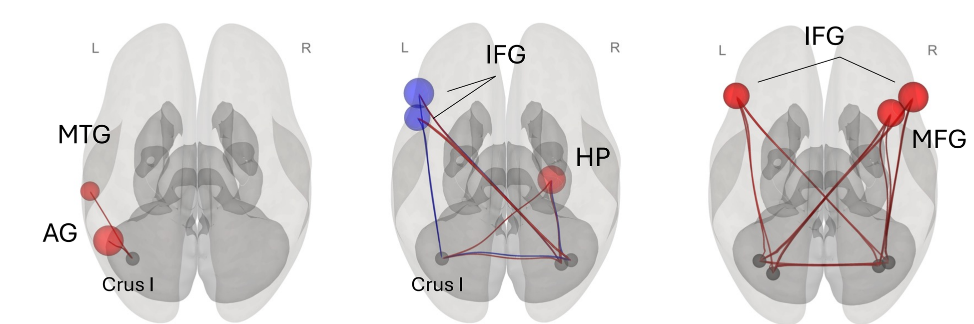
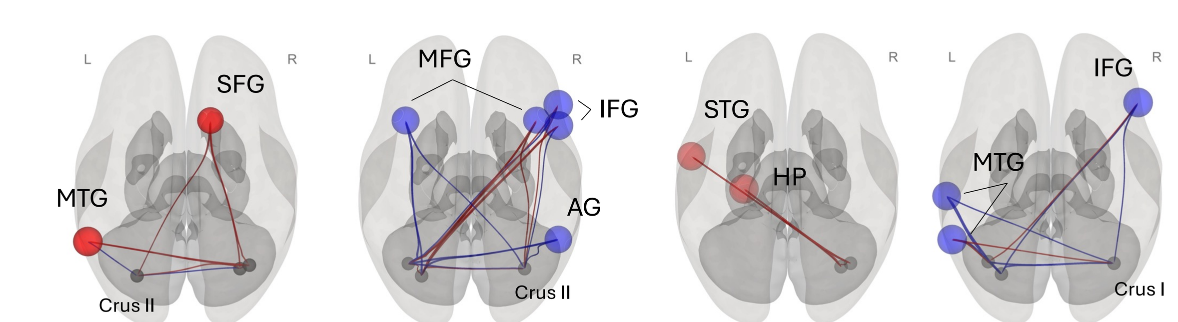
FUNCTIONAL CONNECTIVITY

5 AJ: Positive FC was observed between Crus I/II and language processing areas during word judgment and feedback. During incorrect word pair judgments, Crus I/II became more connected to memory-related regions and less connected to cognitive control areas.



word > rest   word_inc > word_cor   feed > rest

6 GJ: Positive FC was observed between Crus I/II and language and memory-related areas during sentence judgment and feedback. Ungrammatical sentences led to decreased FC with cognitive and executive control regions. Negative feedback is associated with decreased FC between Crus I/II and language processing and cognitive control regions.



sentence > rest   sen_ung > sen_gra   feedback > rest   feed_neg > feed_pos

*Uncorrected $p < .05$ at voxel level, FDR-corrected $p < .05$ at cluster level.

SUMMARY

- The co-activation and FC between the Crus I/II and cerebrum ROIs support the internal model hypothesis, but no significant difference was observed for AJ and GJ. We will further investigate individual difference effects on neural patterns.
- Contrary to our predictions, correct AJ, rather than incorrect AJ, is associated with increased cerebellar activations. However, ungrammatical GJ is associated with increased cerebellar activations but decreased FC between Crus I/II and language processing and cognitive control areas. Negative feedback elicited increased co-activation but decreased FC for GJ.
- These findings suggest that the cerebellum is responsible for executing rather than regulating the internal model during language learning.

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