No evidence for the role of the cerebellum in value-based decision making

Elizabeth Cisneros
Department of Psychology and Neuroscience
University of California, Berkeley
Berkeley, CA 94704
e1cisner@berkeley.edu

Kiely Bol
Department of Psychology
University of California, Berkeley
Berkeley, CA 94704
kielybol@berkeley.edu

Anne GE Collins
Department of Psychology and Neuroscience
University of California, Berkeley
Berkeley, CA 94704
annecollins@berkeley.edu

Sabrina Abram
Department of Psychology and Neuroscience
University of California, Berkeley
Berkeley, CA 94704
abramsabrina@berkeley.edu

Richard B Ivry*
Department of Psychology and Neuroscience
University of California, Berkeley
Berkeley, CA 94704
ivry@berkeley.edu

Jonathan S Tsay*
Department of Psychology
Carnegie Mellon University
Pittsburgh, PA 15213
jtsay2@andrew.cmu.edu

Abstract

The functional domain of the cerebellum extends beyond sensorimotor control, with various lines of evidence pointing to its involvement in a range of cognitive and affective processes including decision making. However, its contributions to human value-based decision-making remain unclear, with prior neuropsychological research involving patients with cerebellar disorders yielding mixed findings. In this preregistered study, we addressed this problem by testing patients with cerebellar degeneration (CD) on a psychophysical task designed to disentangle the contributions of reinforcement learning (RL) and working memory (WM). In the RLWM task, participants used feedback to learn stimulus-response associations. The contribution of WM was assessed by varying the number of stimulus–response associations in the stimulus set under the assumption that WM can support learning for small sets but, due to capacity limits, there is a shift to RL for large sets. To further isolate RL, a test phase was conducted after a 15 min break during which the participants performed a N-back working memory task. This ensured that WM for the learned associations was eliminated due to the passage of time and interference from the N-back tasks. During the learning phase, both CD and healthy controls (HC) exhibited similar performance, with greater accuracy for stimuli from small sets compared to large sets. During the test phase, CD and HC groups performed similarly, with both showing a pronounced decline on small set stimuli. N-back performance also did not differ between groups. Together, these results suggest that the cerebellum may not be critical for value-based decision-making, as well as the RL and WM processes that support it.

Keywords: value-based decision-making, cerebellum, working memory, reinforcement learning

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1 Introduction

While traditionally considered a core node in the sensorimotor control system, the cerebellum is now recognized as a key contributor to a wide array of non-motor functions, including attention, working memory (WM), language processing, and social interaction [1–4]. More recently, behavioral and physiological studies in mice and non-human primates have implicated the cerebellum in reinforcement learning (RL) [4–7].

However, the cerebellum's role in human value-based decision making remains controversial, with neuropsychological involving patients with cerebellar disorders reporting mixed findings: Some have reported marked impairment [8], while others find no impairment [9]. Recent work has highlighted how value-based decision making can involve contribution from both reinforcement learning (RL), a gradual process of learning and updating values tied to objects and actions, and working memory (WM), a rapid, flexible system for maintaining goal-relevant information [10]. Building on this observation, we conducted a pre-registered study, comparing the performance of individuals with cerebellar degeneration (CD) and matched controls on a task that disentangles the contributions of RL and WM in value-based decision- making [10–13].

2 Methods

2.1 Participants

Participants with CD (n = 20; age (mean ± SD) = 60.4 ± 8.5 years, 17 females) and neurologically healthy controls (n = 20; age (mean ± SD) = 60.3 ± 8.2 years, 17 females) participated in the study. Inclusion in the CD group required genetic confirmation of spinocerebellar atrophy or a clinical diagnosis of ataxia. Control participants were age, sex, and education matched to our clinical sample. This study's main hypotheses, experimental design, and key analyses were pre-registered: https://aspredicted.org/5ddw-f5s6.pdf.

2.2 Experimental Protocol

We used the RLWM task to assess the cerebellum's role in RL and WM during value-based decision making [10–13] (Figure 1). In this task, participants use feedback to learn a set of stimulus-response associations. Binary feedback is assumed to engage RL-based learning processes. Moreover, WM has been shown to bolster learning, with the contribution being especially pronounced when the set size is small and thus falls within WM capacity. As such, accuracy quickly reaches asymptote when the set size is small (e.g., 3), but rises more slowly when the set size is large (e.g., 6) due to the operation of incremental RL.

To further distinguish between RL and WM, we tested participants on the stimulus-response associations 15 minutes after the learning phase, and included a different task during the delay to ensure that WM for the learned associations had decayed. Performance during the test phase provides a clean probe of RL contributions to value-based decision making. Given that the contribution of WM during learning is greater for set size 3, we expect a greater performance decline for set size 3 compared to set size 6 during the test phase [10].

Learning Phase: Participants were instructed to learn the key ('T,' 'Y,' 'U') associated with each stimulus to earn as many points as possible. On each trial, a stimulus was shown, and participants had 2 s to respond. Feedback (1 s) followed, awarding +1 point for correct responses or 0 for incorrect ones. There were 10 blocks in the learning phase, with each block involving a different category of visual stimuli (e.g., animals, fruits). The set size was 3 for six of these blocks and 6 for the other four (always starting and ending with a block of set size 3). Each block was composed of 9 presentations of each stimulus, with the order pseudo- randomized to ensure a relatively uniform delay between successive appearances [10, 13]. Blocks of set size 3 had 27 trials and blocks of set size 6 had 54 trials.

N-back: After the learning phase, participants completed a verbal n-back task to provide a 15-minute delay between the learning and test phases, as well as an additional assessment of WM. Four blocks of each N (1, 2, or 3) were performed, with each block containing 17 + N items. The block included 7 target trials (hits), no triple repeats, and no repeats among the first three letters. Each letter was displayed for 2 s, followed by a 0.5s fixation. For the first three blocks, the order was fixed (N = 1, 2, 3); for the remaining blocks, the order was randomized.

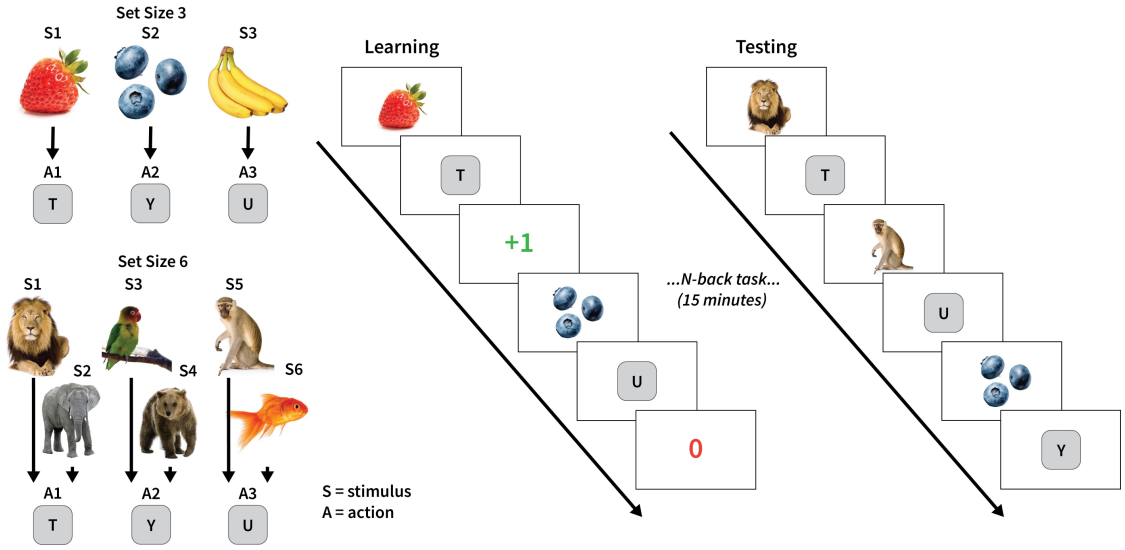

Figure 1. Experimental design. RLWM task with blocks of set size = 3 and set size = 6. In each block, a novel set of stimulus–action associations (3 or 6 stimuli/set) were learned via performance feedback on each trial. Participants were tested on the associations after a 15 min break with no feedback provided on these trials.

Test Phase: At the end of the n-back task, participants were informed that they would now be tested on the stimulus-response associations from the learning phase, a detail not disclosed earlier. This phase consisted of a single block where all stimuli from the learning phase (excluding the first and last blocks to reduce recency and primacy effects) were presented five times each, totaling 165 trials (number of stimuli = 33; 15 from set size 3 and 18 from set size 6 blocks). Stimuli were presented in a pseudo-randomized order to ensure each appeared once in each fifth of the testing phase. The trial structure mirrored the learning phase but omitted feedback to prevent new learning. While WM influences performance during the learning phase, performance during the test phase primarily reflects longer-term memories from RL, since WM is assumed to be disrupted by the delay and intervening N-back task [10]. As such, we expect a greater performance drop from learning to test for the stimuli from the small sets compared to the large sets.

Behavioral analyses: To visualize the learning trajectory, we computed participants' accuracy at each stimulus iteration (collapsed across all stimuli) for each set size. We excluded trials with missing responses. We measured asymptotic performance during the learning phase by averaging performance during the last three stimulus iterations.

3 Results

3.1 Comparable learning performance between groups

Both groups exhibited learning, with the greater improvements seen in the small set blocks (Figure 2A; Main effect of set size: $F(1,40) = 29.68$, $p < 0.001$). For both set sizes, the rate and extent of learning was similar between groups (Figure 2A). That is, average accuracy did not significantly differ between groups (Main effect of Group: $F(1,40) = 0.44$, $p = 0.50$; HC: 0.63 ± 0.16; CD: 0.62 ± 0.17), with similar performance observed for both set size 3 ($t(40) = 0.70$, $p = 0.49$) and set size 6 ($t(40) = -0.11$, $p = 0.91$). There was no interaction between set size and group ($F(1,40) = 0.32$, $p = 0.57$). These results indicate that cerebellar degeneration did not impact value-based decision making during the learning phase.

3.2 Comparable testing performance between groups

In both groups, performance declined in the test phase (Figure 2B). Notably, this decline was much greater for stimuli from small sets compared to large sets (Main effect of set size: $F(1,40) = 23.31$, $p < 0.001$; CD: $t(20) = 5.01$, $p < 0.001$; HC: $t(20) = 5.07$, $p < 0.001$), consistent with the assumption WM had made a significant contribution to learning the associations for the small set stimuli [9]. There was no interaction between set size and group ($F(1,40) = 0.09$, $p = 0.77$) and the asymmetry in set size accuracy decline from the learning phase to the test phase was similar for both groups $t(40) = -0.31$, $p = 0.76$; Figure 2B); thus, the data indicate that WM provided a comparable boost to performance for both groups. While CD exhibited a slight advantage during the test phase

compared to HC, suggestive of greater RL reliance, the group difference was not significant ($t(40) = 0.97$, $p = 0.33$; $d = 0.22$). Together, these results suggest that RL remains intact in individuals with cerebellar degeneration.

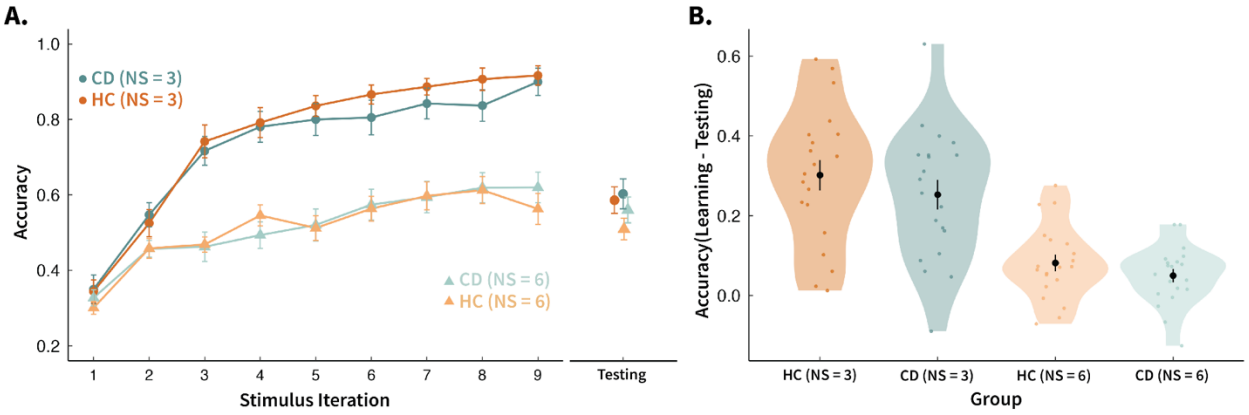

Figure 2. No evidence for the role of the cerebellum on value-based decision making. (**A**) Learning curves for both set sizes in cerebellar degeneration (CD; N=20; teal) and healthy controls (HC; N=20; orange) along with proportion of correct trials during the testing phase. (**B**) Difference between proportion of correct trials at asymptotic learning performance (last three stimulus iterations) and during test phase. Black dot denotes the group mean. Translucent dots represent individual participants. (**A, B**) Error bars denote standard error.

3.3 Intact N-back Working Memory Performance in Cerebellar Degeneration

For the n-back task, we restricted our analysis to set sizes 2 and 3, as a greater proportion of participants reached ceiling performance on n-back 1. We also consider n-back 1 to primarily reflect attentional processes, whereas higher n-back levels provide a better measure of working memory. As expected, performance on the n-back task was inversely related to N for both groups (main effect of n-back size, $F(1,78) = 9.64$, $p = 0.004$; Figure 3A). There was no significant effect of group on d' scores (main effect of Group, $F(1,78) = 2.4$, $p = 0.13$). The interaction between Group and n-back size was not significant ($F(1,78) = 1.29$, $p = 0.26$).

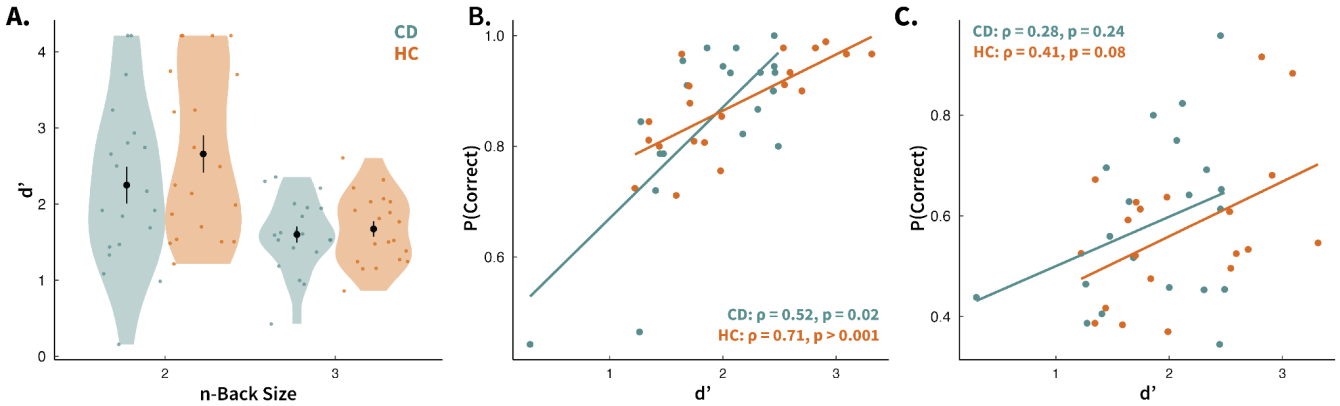

Figure 3. Intact n-back working memory performance in cerebellar degeneration. (**A**) Average performance in the n-back task (d') for each n-back size. Black dot denotes the group mean; error bars denote standard error. Translucent dots represent individual participants. (**B,C**) Correlation between performance in the n-back task (averaged for each individual over the 3 n-back conditions) with early learning performance (first three stimulus iterations) for (**B**) set size 3 and (**C**) set size 6. CD and HC correlations are shown in teal and orange, respectively.

3.4 Verifying the role of working memory in value-based decision-making

As discussed above, performance in the small set condition is more dependent on WM. Given this, we predicted that performance on the n-back task would be correlated with early learning for set size 3, but not with set size 6. The results were consistent with this prediction (Figure 3B-C, Small Set: CD: $\varrho = 0.52$, $p = 0.02$; HC: $\varrho = 0.71$, $p > 0.001$; Large Set: CD: $\varrho = 0.28$, $p = 0.24$; HC: $\varrho = 0.41$, $p = 0.08$). The correlational analyses reaffirm that value-based decision-making relies not only on RL but also on WM, with WM playing a larger role when set sizes are below capacity.

3.5 RLWM task performance related to cognitive task but not CD motor severity symptoms

All participants completed the Montreal Cognitive Assessment (MoCA) to provide a general measure of cognitive status. This assessment is scored out of 30, with higher scores reflecting better cognitive function. There was no significant difference in MoCA scores between participants with CD and HC ($t(40) = 1.76$, $p = 0.09$; HC: 28.2 ± 1.8; CD: 27.0 ± 2.3). For participants with CD, we also administered the Scale for the Assessment and Rating of Ataxia (SARA), which is scored out of 40, with higher scores indicating greater motor impairment. Participants with CD showed low to moderate levels of motor impairment (Mean $\pm$ SD: 15.0 ± 8.6).

In patients with CD, RLWM task performance was positively correlated with both n-back performance ($\varrho = 0.67$, $p = 0.006$) and MoCA scores ($\varrho = 0.67$, $p = 0.006$). MoCA scores were also positively correlated with n-back performance ($\varrho = 0.72$, $p = 0.002$). In contrast, SARA scores were not significantly correlated with any of these measures (RLWM accuracy: $\varrho = -0.45$, $p = 0.09$; n-back: $\varrho = -0.49$, $p = 0.09$; MoCA: $\varrho = -0.44$, $p = 0.09$). This indicates that individual differences in RLWM performance are more closely linked to general cognitive function than to motor severity in CD.

4 Conclusion

We took a neuropsychological approach to ask whether the cerebellum plays a role in value-based decision making. Our results indicate that despite cerebellar degeneration, participants showed no impairment in verbal working memory, reinforcement learning, or their integration during value-based decision-making. More specifically, our patient sample performed comparably to controls on the RLWM task. In future work, we will incorporate computational modeling to further examine the distinct contributions of WM and RL to value-based decision making, and how these processes may be preserved or subtly altered in cerebellar degeneration.

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