

Can you teach an old monkey a new trick?

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Summary

Understanding how learning differs between groups of subjects is important in many areas of neuroscience. Obtaining an objective measure can be challenging because learning is dynamic and varies greatly between individuals. We introduce a method for analyzing two-dimensional (2D) binary response data from monkeys performing a sequence of tasks across multiple days that enables us to compare performance between two age groups. The data were obtained from 14 female macaque monkeys (6 young) performing a reversal learning task—a modified Wisconsin Card Sort Task. Conventional methods ignore the 2D nature of these data by aggregating the responses across days or tasks, thus failing to capture subtle changes in learning dynamics. We propose a separable 2D random field (RF) model wherein the probability of making correct choices on a given day depends on two latent Markovian state sequences that evolve separately but in parallel. We use a Laplacian prior for the latent process capturing the learning dynamics across days which, unlike its Gaussian counterpart, allows abrupt transitions such as occur in reversal learning. An efficient Monte Carlo Expectation-Maximization algorithm is employed to estimate the parameters of the RF by maximum likelihood, followed by a provably convergent iteratively re-weighted least-squares Maximum a Posteriori algorithm for change point detection. The approach obviates the need for aggregating across either of the dimensions, produces a within-day performance metric by task for each group, and a learning rate across days for each monkey. We show that the older monkeys find the tasks harder, and that the cognitive flexibility (ability to successfully relearn tasks after reversal) of the younger group is higher. Further demonstrating the strength of our method, we show how the monkeys can be clustered based on a cognitive flexibility metric computed from our model.

Additional Details

We model the dynamics of learning from each group of monkeys separately, each as a 2D random field

$$\begin{cases} d_k = d_{k-1} + \delta_k, \delta_k \sim \mathcal{N}(0, \sigma_\delta^2) \\ x_r^m = x_{r-1}^m + \epsilon_r^m, \epsilon_r^m \sim \mathcal{Laplace}(0, \lambda^m) \\ \pi_{k,r}^m = \frac{e^{x_r^m - d_k}}{1 + e^{x_r^m - d_k}} \\ \Delta N_{k,r}^m | d_k, x_r^m \sim \text{Bernoulli}(\pi_{r,k}^m) \end{cases}$$

where $(d_k)_{k=1}^K$ is a group-level latent sequence that represents the group performance on object pairs presented within a day and $(x_r^m)_{r=1}^{R_m}$ is the latent state of learning for monkey number m across days. Responses are denoted by $(\Delta N_{k,r}^m)_{k=1,r=1}^{K,R_m}$ which is 1 if monkey m produces a correct response when presented object pair k on day r , and 0 otherwise. Across days each animal is allowed its own personal learning curve which results in a latent state sequence $(x_r^m)_{r=1}^{R_m}$ for each monkey. There are total of $K = 40$ object pairs, and the total number of days R_m of the experiment depends on the animal [1].

Figure 1 shows typical response data for a young monkey (a) and an old monkey (b). The panel below each raster shows the latent state representing the within-day performance for each object pair for each age group (replicated on each panel for comparison purposes). The panel on the left of each raster shows the estimated latent state representing each monkey’s individual learning process.

Between-group differences within a day: The lower panels of Figure 1 (a) and (b) show that the old monkeys find the tasks harder than the young monkeys. Our algorithm allows us to compute the posterior distribution of performance within day for each group, allowing us to compare groups’ within day performance. This computation (not shown) revealed that the curves in Figure 1 (a) and (b) are significantly different. Both age groups display the same trend: the object pairs in the middle appear easier to remember than the object pairs at the start and end. This effect was previously observed

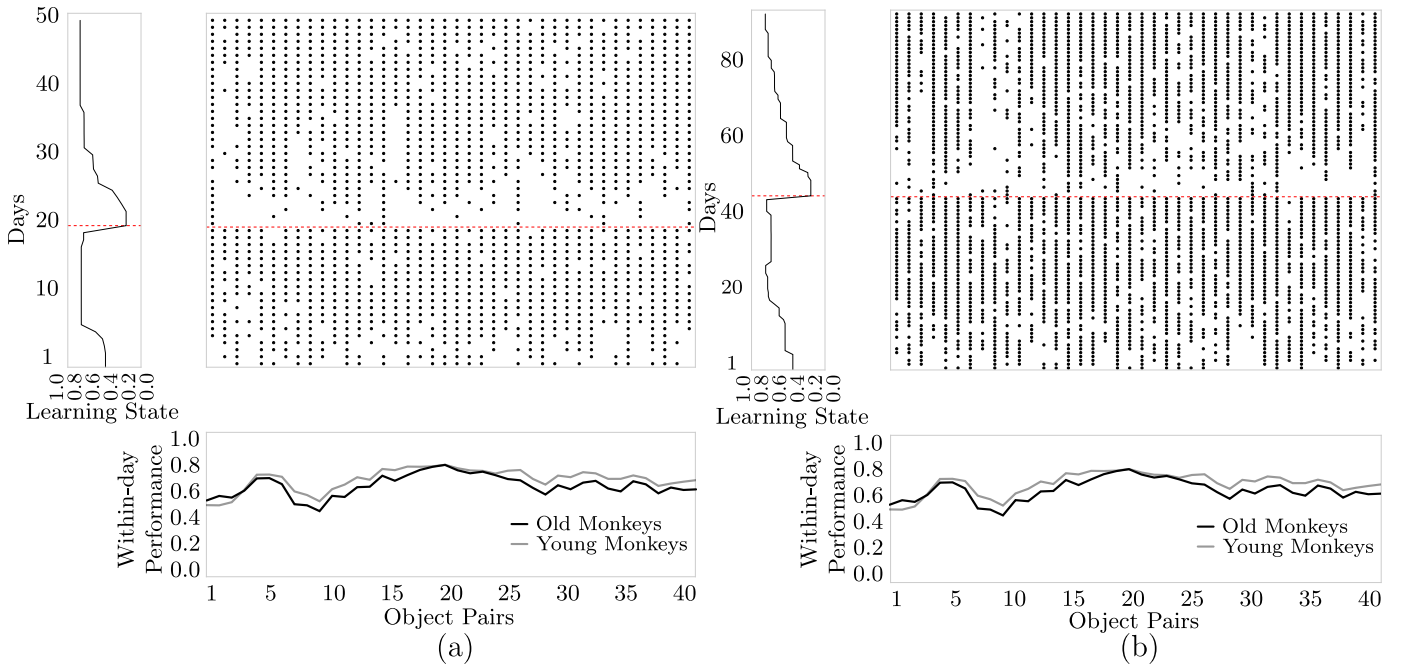


Figure 1: Performance raster and hidden latent states for a young monkey (a) and an old monkey (b). The horizontal red line indicates the task reversal.

when both groups were combined. Since this current approach allows more detailed examination of learning of individual object pairs, we are able to detect significant between-group differences.

Between-group differences across days: The model provides an individual learning curve for each animal (Figure 1 (a) and (b), left panels). Figure 1(b) indicates that the older monkey takes longer to learn the task both before and after the reversal. The Laplacian prior allows accurate identification of the drop in performance after the object pairs are reversed (red line).

We assess the ability of a monkey perform the task after reversal, by computing a “cognitive flexibility” measure, defined as the difference between the average rate of change of learning before and after the reversal, using samples from the posterior distribution of the learning state of each monkey. A given monkey is more flexible than another monkey if, with high probability, her cognitive flexibility is higher than that of the second monkey. Figure 2 shows, in the form of a clustered heatmap, a comparison of the cognitive flexibility of all pairs of monkeys. A dark/light color indicates the probability that cognitive flexibility of the monkey listed on the y-axis is higher/lower than the cognitive flexibility of the monkey listed on the x-axis. Red indicates that this probability is higher than 97.5% and yellow suggests it is under 2.5% (older monkeys: 1–8, younger monkeys: 9–14). The dark section in the upper right corner indicates that the cognitive flexibility of younger monkeys (in addition to one old monkey, #8) is generally higher than older ones. This is confirmed by looking at the dendrogram which clusters the animals into two groups: all young monkeys with # 8, and all old monkeys not including # 8. This suggests a powerful technique for extracting age based on raw performance.

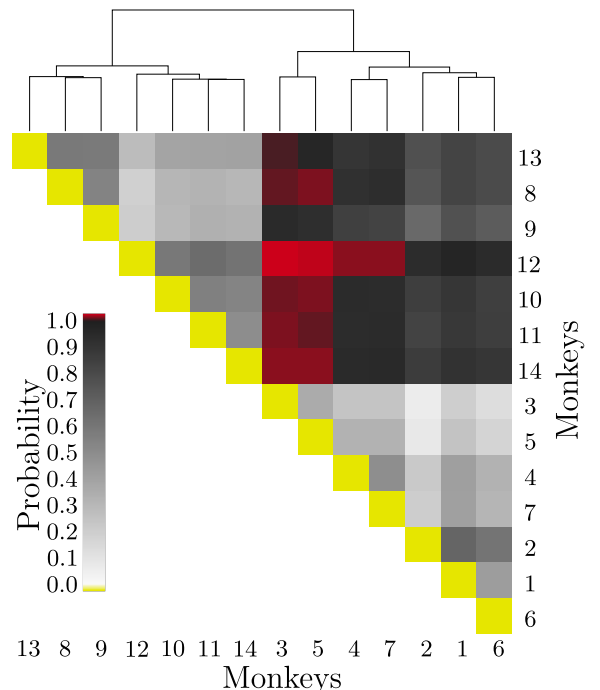


Figure 2: Between-subject cognitive flexibility comparison.

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[1] Daniel T Gray et al., Attentional updating and monitoring and affective shifting are impacted independently by aging in macaque monkeys. *Behavioural Brain Research*, 2016.