Neural signatures for temporal-order memory in the medial posterior parietal cortex

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SUMMARY

Episodic memory involves encoding and remembering the order of events experienced over time. Previous work examining the mechanisms of temporal-order memories has focused on the hippocampus and prefrontal cortices but has largely ignored the memory ensembles in the medial posterior parietal cortex (mPPC). Combining *in vivo* multi-unit electrophysiology and a temporal-order judgment task with cinematic material in the macaque, we find that mPPC neuronal activity reflects temporal context both during encoding and recall. During learning, mPPC neuronal ensembles encode the temporal information embedded in the videos, whereas at retrieval these neurons fire in synchrony prior to memory-guided decisions. Moreover, the similarity between encoding and retrieval correlates with the animal's performance. Together, these data suggest that neuronal activity in mPPC underpinning temporal-order memories.

KEYWORDS

Temporal context cells, precuneus, nonhuman primates, spike train synchrony, memory retrieval, episodic memory, evidence accumulation, temporal-order judgment, encoding-retrieval neural similarity

INTRODUCTION

Remembering the temporal order of experiences is a fundamental feature of episodic memory [1–4]. Ample research has implicated the MTL in different aspects of temporal memory, with evidence from a large number of studies suggesting that neural activities in the MTL, especially the hippocampus, mediate the formation of temporal order memories [5–10], potentially via sequence generation [11]. While temporal information about past events may be present within the hippocampus [12–14], data also suggests that the computation for temporal memory and order of events may also involve the lateral PFC [15,16] and/or the posterior parietal cortex [17,18]. Given the precuneus' role in temporal context [19], temporal memory [20] as well as in forming new memories [21,22], the mPPC may be expected to serve as a plausible neural hub in the computation for the retrospective remembering of temporal order of experiences.

Theorists posit that successful memory of temporal order necessitates the brain linking temporal contextual information across memory phases. According to the temporal context model [23–25], when multiple events occur close together in time, they generate multiple sequences across the overall population which may overlap with each other depending on the temporal distance between these events. These sequences provide a readout of recent events and their temporal history. Empirical evidence on time cells and temporal context cells that can encode the passage of time and organize incoming information [26] corroborate the predictions of these theories for the encoding phase of the experiences. However, while the temporal coding properties of "time cells" offer a suitable mechanism by which time may be encoded, it is not clear whether and how such temporal context signals [26] established at encoding would later be reactivated and utilized to help determine the temporal order for different episodes of experience at retrieval.

To address these questions, we recorded multi-neuron activities from the monkey mPPC (the precuneus) while the animals made temporal order judgment of two still frames extracted from encoded videos. We found that neurons in the mPPC encode the passage of time and engender a spectrum of time contextual constants during encoding (videos) and similar pattens of activity are reinstated during the subsequent recollection of memories, with synchronous neuronal activity reflecting the accumulation of mnemonic information for higher memory accuracy.

RESULTS

Forward memory search during temporal order judgment of cinematic events

After watching an 8-s naturalistic video, monkeys performed a temporal order judgment task during which they were required to judge the earlier frame among two frames extracted from the video. We controlled for temporal similarity for the two conditions, thus having two delayed conditions here: immediate TOJ for frames taken from first half of the video (5th and 90th frames) vs. delayed TOJ for frames taken from latter half of the video (95th and 180th frames), Figure 1A. The performance of both monkeys was significantly higher than the chance level and remained steady through the experiment for the two conditions (Jupiter: immediate = 66.6%, delayed = 69.8%; overall mean = 67.7%, against chance $P < 0.001$, Mercury: immediate = 62.7%, delayed = 69.8%, overall mean = 64.2%, against chance $P < 0.001$), Figure 1C. We then compared the RTs under different chosen frame locations and replicated our previous results [27], finding that RTs were faster for frames chosen from the early part of the video (one-

way ANOVA, Jupiter: $F(3, 10171) = 52.91$, $P < 0.001$, post hoc test, 5th frame vs 90th frame, $P < 0.001$, 95th frame vs 180th frame, $P < 0.001$; Mercury: $F(3, 3195) = 5.86$, $P < 0.001$, post hoc test, 5th frame vs 90th frame, $P = 0.006$, 95th frame vs 180th frame, $P = 0.041$) and a numeral trend of increased RTs as a function of the four chosen frame locations (Figure 1D).

Identification of temporal context cells during encoding period

First, we asked if mPPC neurons are involved in the temporal memory encoding. We set out to find temporal context cells that help code for time and build a temporal contextual record of the past [26]. To examine whether mPPC involved in the representation of temporal context information (cf. temporal context cells in monkey entorhinal cortex [26,28]), we fitted the spike data during the encoding period (videos) with three different models for each neuron (see 'Temporal context cell fitting' in STAR Methods). We first fit the firing pattern of each cell with a convolution of Gaussian and an exponential function [26]. There are two key parameters that would determine the shape of distribution. One parameter is the mean of Gaussian μ, which indicates the response latency of each neuron. Another parameter is the time constant of the exponential function τ, which represents the time each neuron needs to relax back to 63% of the peak firing rate (relaxation time). For comparison, we also fitted our data with the constant model and the Gaussian model. Using the likelihood ratio test for model comparison, we identified 111 neurons (out of 676) as temporal context cells. Among those temporal context cells, 63 neurons increase their firing rate at the beginning of video (see an example neuron in Figure 2A, left), while 48 neurons decrease their firing rate (Figure 2A, right). The normalized firing rate pattern for the whole population of temporal context cells shows that most neurons in mPPC reacted to the video material within a short period of time (Figure 2B). When we looked at the relationship between the cells' response latency and their relaxation time, a majority of the neurons respond to the video onset within 1 s and decrease their firing rate with different latency ranging from 0 s to a hypothetical 20 s (Figure 2C), highly resembling the patterns previously reported for entorhinal temporal context cells [26].

Cell ensembles carry information about passage of time in video

We next assessed how these neurons represent the passage of time during encoding as a population. We trained a linear discriminant analysis (LDA) decoder to estimate the time following the presentation of a video. To the extent the predicted time bin for out-of-sample data is close to the actual time bin, we infer that the population response carried information about time. In each trial, we took 250 ms as the time bin and divided each 8 s video into 32 bins. We trained the classifier with odd trials and tested the temporal information in even trials. The LDA results show that the mean absolute decoding error (Jupiter: 1.58 s; Mercury: 1.60 s) was reliably lower than the decoding error after 1000 permutations (Jupiter: mean = 2.661 s, SD = 0.183 s, z score = -5.907; Mercury: mean = 2.664 s, SD = 0.199 s, z score = -5.347, Figure 3A-B, D-E). When we looked at the decoding error in each time bin, the decoding error of the first 1s time bins was much lower than the rest of the time bins for both monkeys (Figure 3C, F). To ensure that the decoding results are not contaminated by the initial period of video, we repeated the LDA analysis but now cut the time bins from the start of encoding at the step of 0.5 s. This control analysis shows that the absolute decoding error was still significantly lower than permutation errors (Figure S2), implying that the mPPC neurons carry information about the temporal unfolding of the videos.

mPPC neurons mediate TOJ processes

We then verified whether mPPC neurons code for memory during temporal order of judgement. Given the region's role in memory recollection [29], we expected to observe neuronal signals to be related to memory processes and performance. To address this question, we ran a Poisson GLM taking into account the within-session block number, reaction time, response outcome (correct vs incorrect), conditions (immediate vs delayed condition), touch side (left vs right), and average firing rate of each event within a trial including preparation, encoding period, delay period, TOJ period, feedback (reward vs blank), and ITI period and identified the neurons that are significantly responsive to the TOJ event, which we refer to as "TOJ cells" (n = 447). Together with the non-TOJ neurons (n = 229), we fisher transformed their GLM coefficients (adjusted R^2 values) into normal distribution and confirmed that the R values are significantly larger for the TOJ cells than for non-TOJ cells (Jupiter: two-sample t-tests, t (399) = 7.806, P<0.001, Cohen's d=0.793; Mercury: t (273) =16.640, P<0.001, Cohen's d=2.029) (Figure 4A). Moreover, when we examined the firing rate for correct trials versus incorrect trials during the TOJ period, 72 (~10.7%) neurons differed in their firing rates between correct response and incorrect response (one-tailed t-test, all Ps<0.05). There were two types of neurons: one type that increased its firing rate for correct decisions (n = 36, Figure 4B) and another one that increased its firing rate for incorrect decisions (n = 36, Figure 4C**)**. This opposing response pattern has been previously reported in hippocampal neurons for repeat vs. novel still images [30].

Spike train synchrony tracks evidence accumulation for TOJ decision

Given that mPPC neurons are involved in memory retrieval, we next examined the their activity during the recall period. We took the temporal dynamics (relative spike timing) across the spike trains of multiple neurons into consideration to reveal how spike synchrony tracks the processes of temporal order judgment. We calculated real-time SPIKE-distance based on the temporal information of firing for all neurons recorded within a session [31], with lower SPIKE-distance values reflecting greater synchrony, examining the degree of synchronous activity time-locked to either the TOJ onset (i.e., when two probe frames shown on screen) or the TOJ response offset (i.e., when the monkey made the decision). During the TOJ onset period, the synchrony level increased and reached its peak within 200 ms, indicating that mPPC neurons work in concert in a progressive manner after the probe frames initiated the retrieval process. This spike train synchrony asymptotes very quickly (< 200 ms), but we did not observe persistent differences in correct vs. incorrect responses during this initial period (Figure 5A-B top). In contrast, during the time just prior to the monkeys' responses (TOJ offset), the synchrony level in correct trials is significantly, and persistently, higher than in incorrect trials as the monkey's decision time approaches (Figure 5A-B bottom), indicating that the population synchrony is stronger during successful TOJ decisions. This is a continual process with statistical differences more densely observed 400-500 ms prior to manual responses made by the monkeys, implying the neurons fire in synchrony to regulate the accumulation of mnemonic information and result in higher memory accuracy. Additionally, we observed differences in the pattern of synchrony level during the TOJ period for both the immediate and delayed conditions. The synchrony level is consistently higher for the delayed condition compared to the immediate condition both time locked to TOJ onset (Figure 5C-D top) or at monkeys' responses (Figure 5C-D bottom). Since memory traces for trials without a retention delay ought to be stronger than those with a longer retention delay, these data imply

that a high synchronization among spike trains is a neural proxy for memory strength.

Similarity of neural activity between encoding and retrieval reflect temporal memory judgment

Since encoding-retrieval neural similarity has been reported to modulate memory success [32,33], we used the population-based similarity to quantify the link between the encoding and retrieval phases of the task. For each trial, we constructed N-dimensional population vectors for the firing rate of encoding and retrieval period respectively (N refers to the number of neurons recorded in that session). Mahalanobis distance was calculated between the population vector of encoding and retrieval periods as a measure of dissimilarity in the pattern of firing across the two stages. To compare the Mahalanobis distance across sessions with varying number of cells (ranging from 5 to 21 neurons per session), we divided the Mahalanobis distance by two times the number of cells in that session and obtained a Distance Index [6]. As evidenced in several example trials, the Mahalanobis distance was consistently smaller during correct trials (Figure 6A). Indeed, two-samples *t*-tests revealed a significant lower Distance Index (that is, more similarity) for correct trials (Jupiter: mean = 0.517, SD = 0.726; Mercury: mean = 0.913, SD = 0.543) than incorrect trials (Jupiter: mean = 0.664, SD = 0.701; Mercury: mean = 1.086, SD = 0.821) (Jupiter: one-tailed $t_{10405} = -9.722$, $P < 0.001$, Cohen's d = -0.206, 95% CI: -Inf to -0.122; Mercury: one-tailed $t_{3605} = -7.589$, $P < 0.001$, Cohen's d = 0.249, 95% CI: -Inf to -0.135; Figure 6B). Our finding of spike pattern reinstatement during TOJ aligns with data from single neurons in human patients that suggest the population states observed during initial experience are reinstated during subsequent recall [34–36]. Overall, we showed that mPPC neurons carry memory related information and their engagement in encoding-retrieval neural similarity supports successful memory for temporal order of video events.

Finally, we examined the relationship between the temporal context cells and their functional relevancy with memory recollection of temporal order. We identified the TOJ cells (see above) that are also classified as temporal context cells, observing that ~70.3% (78 out of 111 cells) of the temporal context cells belonged to the class of TOJ cells (Figure 6C). Since these neurons were involved in the encoding of temporal context, we expected these cells to be resistant to relaxing to the baseline to facilitate a fuller encoding of the whole range of temporal context for the videos. To test this, we compared the relaxation time between those 78 TOJ ∩ temporal context cells (relaxation time: mean = 5.150 s SD = 4.407) and the remaining 33 non-TOJ ∩ temporal context cells (mean = 2.082 s, SD = 6.727) but this comparison did not result in statistical significance (p = 0.229; Figure 6D). It is possible that these cells as a whole cover a broad spectrum of time, thereby flexibly representing the temporal contextual information embedded in the videos. These data demonstrated that beginning with the video onset mPPC neurons form and utilize prior temporal context at encoding to support the subsequent TOJ.

DISCUSSION

In this study, we examined the role of mPPC neurons during the encoding and retrieval process of temporal order judgment. We found that mPPC neurons are strongly involved in both the encoding and retrieval of temporal information of events embedded in video material, with these neurons work in synchrony to enable successful judgment of temporal order. By identifying a subset of neurons that code for context within episodes, we found that neural coding for temporal context during experience may provide a scaffold for subsequent memory of event order. Below we discuss several implications of our discoveries.

We elucidated the neural activities for the memory traces during encoding and how they might be related to the activities upon retrieval. Inspired by the recent discovery of temporal context cells in the primate entorhinal cortex [26], we found a subset of mPPC neurons, labelled as temporal context cells, respond to the video context at the time of onset, but relaxing to baseline at different rates. This property has previously been shown in the entorhinal cortex [26] when still picture stimuli were used. Compared to static pictures, dynamic videos in the current set-up simulate contextual information more ecologically. We further found that over two-thirds of the temporal context cells belonged to the class of TOJ cells and that they cover a wide spectrum of relaxation time. A population of temporal context cells with highly variable lengths of relaxation time could work as an instrumental encoding mechanism to process and encode the video experience as a coherent event [37,38]. Since different neurons decay at a variety of rates, the animal could infer how far in the past certain frames were by processing which cells were active at which point. Howard and colleagues suggest such spectrum of time constants enable the brain to represent a Laplace transform of the organism's past [26]. This spectrum-based temporal record of the past has previously been observed in hippocampal neurons, which hold incremental timing signal for separate items within an event [39]as well as code for temporal-order relationships between events [40,41].

Another interpretation of the significance of such variable relaxation time could be related to the notion of temporal receptive windows [42,43]. This phenomenon stipulates that cortical activities are organized in a hierarchical manner, with prefrontal and parietal areas exhibiting longer timescales [43]. Converging with this idea, we trained a decoder to reveal that these neuron ensembles carry information about the passage of time embedded in the videos. We infer from the successful decoding of the second-by-second within-video temporal information that the mPPC neurons reflect information about the temporal unfolding of events across an extended window. This finding aligns with previous fMRI, single-unit, and electrocorticography evidence that suggests that cortical circuits can accumulate information over time following a hierarchical arrangement from early sensory areas with short processing timescales to higher-order areas such the mPFC and the mPPC hub with long processing timescales [43,44].

We next sought to understand the mechanisms of mPPC involved in temporal memory retrieval by examining the single and ensemble neuronal activities. We found that a subpopulation of mPPC neurons which were identified as TOJ cells modulated their activity specifically when monkeys were judging the temporal order of probe frames. Further, this neuronal activity was modulated by the correctness of response, implying the role of this brain region in memory retrieval. These findings align with fMRI studies identifying a similar function of mPPC during memory retrieval [17,18]. Solely based on

fMRI data, it is difficult to explore the underlying mechanism of how mPPC is involved in the reinstatement and recollection of temporal order memory [45]. By contrast, we looked specifically into the temporal dynamics under TOJ memory recall and found that the level of neuronal synchrony increased gradually when temporal judgment was initiated. Irrespective of the memory outcome, the synchrony level of neuronal spikes peaked rapidly around 250 ms, indicating that decision evidence could be accumulated in a rapid manner, in line with effects reported in decision making [46], spatial [47] and working memory [48]. Moreover, when we focused on the window leading to the moment of decision, we observed that correct decisions would trigger a significantly higher synchrony level of mPPC populations than incorrect trials immediately before the moment of decision. The effect is akin to the findings reported in the inferotemporal cortex where neuronal synchrony is enhanced for successful recognition of visual stimuli [49], implying that synchrony level of population determines the processes towards a correct decision [50]. Additionally, we found that the neuronal synchrony level is higher for trials without a retention delay than for trials with a longer retention delay. These provided compelling evidence that the synchrony among the parietal neurons is an indicator of memory strength [51] of temporal-order information.

To link it with the wider literature on temporal memory, we acknowledge a series of work that has indicated how cells in the hippocampus are recruited for encoding temporal information [16,39,52] and function as schema/event cells across extended time for experiences/memory [53]. Multiple memory systems are also possible to support temporal-order memory (e.g., with orbitofrontal cortex[54,55] and contextual representation of events [56]. One of the paths for future investigation should be focused on the interplay between MTL (e.g., time cells), medial parietal region [57], and the prefrontal region [16].

FIGURE LEGENDS

Figure 1 Paradigm, recording system and sites, and behavioral results.

(A) Temporal order judgment task. In each trial, the monkey watched an 8-s video, and following a 3.6-s delay or 0-s delay, the monkey judged which frame they had seen earlier to get a reward.

(B) Upper panel: the position of recording electrodes in the mPPC shown in blue on an MRI image. Bottom panel: CT image aligned with MRI image taken at the beginning of the experiment.

(C) Accuracy percentage across all sessions for all trials (green star), immediate condition (cyan square) and delayed condition (magenta triangle) of Jupiter and Mercury.

(D) Mean reaction times of different chosen frame locations for the two monkeys. *** $P < 0.001$, * $P < 0.05$.

Figure 2 Temporal context cells during encoding (video) period.

(A) Two examples of temporal context cells during video-watching period. Spike raster (upper) and peristimulus time histograms (PSTHs, lower) plotted against the onset time of video-watching. In the PSTHs, the solid black line indicates the smoothed firing rate. The dash pink line, the dash blue line, and the dash black line indicate the fitting result of the ex-Gaussian, gaussian and constant model respectively. Relaxation time means the time interval between peak firing rate and when the neurons returned 63% of the way to baseline. The example on the left increases its firing rate at the beginning of video, whereas the example on the right decreases its firing rate.

(B) A heat plot of the normalized firing rate of 111 temporal context cells, relative to video onset, sorted by their relaxation time. Some neurons relaxed back to baseline slowly, covering the whole duration of the video, but overall, the neurons relaxed back to baseline with a broad spectrum of decay rates.

(C) The plot of each temporal context cell's response latency and relaxation time. The response latency of all temporal context cells is less than 1s, while the relaxation time range from 0 to 20 s. The dots indicate temporal context cells recorded from monkey Jupiter (66 neurons, orange) and monkey Mercury (45 neurons, purple) respectively.

Figure 3 mPPC neurons encode passage of temporal information in videos.

(A) For monkey Jupiter. Decoder performance trained on the entire population of mPPC neurons. The x-axis indicates the actual time bin, and the y-axis indicates the decoded time. Each time bin represents 250 ms of the video, and each 8-s video was divided into 32 bins. The grayscale indicates the posterior probability in the logarithmic scale, with a lighter shade indicating higher probability. The decoded time with the highest probability in each time bin is marked with a red dot. Each second was marked with red arrows along the axis.

(B) The actual decoded errors are shown by a vertical line (1.58 s for Jupiter, 1.6 s for Mercury) and the distribution of errors obtained from 1000 permutations. In both monkeys, actual errors are significantly smaller than the errors by permutation, indicating a successful decoding.

(C) The mean absolute decoding error value in each time bin. For both monkeys, the error was relatively lower at the beginning of the video (around first 0.5 s; see also Figure S2).

(D) – (F) same as (A-C) for Mercury.

Figure 4 TOJ cells and neuronal activities reflecting memory correctness for temporal order judgment.

(A) Histogram of R^2 values from stepwise GLM for TOJ cell (cyan) and non-TOJ cell (Brown) of two monkeys. There are 278 TOJ cells and 123 non-TOJ cells for Jupiter and 169 and 106 cells for Mercury, respectively.

(B) An example neuron that showed higher firing rates for correct trials than incorrect trials (one-tailed t-test, P = 0.027). Left panels show the raster display of the neuron's spike activity in correct trials (Top-left) and incorrect trials (Bottom-left). Top right panel shows the mean response of the example neuron in both correct trials and incorrect trials. Mean firing rates in correct and incorrect trials are shown in black and red, respectively. Bottom right panel shows the group average (n = 36).

(C) Same as (B), but with an example neuron that showed higher firing rates for incorrect trials than correct trials (one-tailed t-test, P = 0.003). Bottom right panel shows the group average (n = 36).

Figure 5 Multivariate SPIKE-profiles at TOJ tracks the process of memory retrieval and support forward search.

(A) – (B) Upper panels show the fluctuation of spike trains synchrony during TOJ. We time-locked 0 ms to the onset of TOJ images. Lower panels show the dynamic of spike trains synchrony with zero time-locked to the moment when a TOJ decision response was made (1000 ms before to 500 ms after a TOJ decision). Black lines show the mean value of SPIKE-distance in correct trials, while red lines represent those for incorrect trials. Green dots at the bottom of each panel indicate a significant difference between correct and incorrect trials for the 10-ms time bin (paired samples t-tests, $P < 0.01$). We also noted a divergence in SPIKE-distance after the response, which might be attributed to post-decision, non-mnemonic processes. Shaded areas represent SEM across sessions.

(C) – (D) We compared the spike trains synchrony for the two experimental conditions (immediate vs. delayed condition) for the two monkeys. The synchrony level is consistently higher for the delayed condition than for the immediate condition. Legends are the same as (A-B).

Figure 6 Population based Mahalanobis distance and TOJ cells ∩ temporal context cells overlap.

(A) Examples of pattern changes across encoding and retrieval within one session. The data in these panels is taken from trial 51, trial 71, and trial 111 of session 41 of Jupiter illustrating the population activity from encoding and TOJ period. The numbers shown are the Distance Index between the two periods for each trial.

(B) Similarity of ensemble responses for correct and incorrect trials. Incorrect trials show a higher Distance Index value than correct trials, indicating higher pattern similarity between encoding and retrieval is crucial for successful memory recall. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

(C) Venn diagram showing the cells (78 cells) that overlapped between temporal context cells (111 cells) and TOJ cells (447 cells).

(D) A heat plot of the normalized firing rate of 78 cells overlapped between the temporal context cell and the TOJ cell.

STAR* METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental Models: Organisms/Strains		
Rhesus macaques (*Macaca mulatta*)	Beijing Institute of Xieerxin Biology Resource	http://www.xexbio.com/cn
Software and Algorithms		
SPIKY		http://www.fi.isc.cnr.it/users/thomas.kreuz/sourcecode.html
neuroGLM package for Matlab	Reference[58]	https://github.com/pillowlab/neuroGLM
MATHEMATICA 12.1		
Slicer 3D v 4.10.2	Reference[59]	https://www.slicer.org
Freesurfer		https://surfer.nmr.mgh.harvard.edu/
MATLAB R2020b	MathWorks	https://www.mathworks.com/
Others		

RESOURCE AVAILABILITY

Lead contact. Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Sze Chai Kwok (sze-chai.kwok@st-hughs.oxon.org).

Data and code availability. Analysis code and processed data supporting the conclusions of this study are available upon request.

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Subjects. Two male rhesus macaques (*Macaca mulatta*) (5 and 5.5 years old, weighing 10.4 and 14.1 kg) participated in this study. The monkeys were usually housed in pairs but were singly housed during the period of this study. They were kept on a 12:12 (7:00am/7:00pm) light-dark circle and kept within the temperature range of 18 - 23°C and humidity between 60% - 80%. The animals were fed twice a day with each portion of at least 180g monkey chow and pieces of apple (8:30 am / 4:00 pm). Water was restricted during recording days. The two monkeys were well trained in performing temporal order judgment tasks prior to this study [27,60]. All animal care, experimental, and surgical procedures were approved by the Institutional Animal Care and Use Committee (permission code: M020150902 & M020150902-2018) at East China Normal University.

Surgery. Each monkey's magnetic resonance image was used to plan the placement of recording chambers. Separate surgeries were performed to implant a head post; then months later, a recording chamber (Gray Matter Research). The recording chambers were placed over the mPPC for both monkey Jupiter (AP = 15.422 mm, ML = 7.549 mm; AP, anterior-posterior; ML, medio-lateral) and monkey Mercury (AP = 16.4 mm,

ML = 5.8 mm). MRI with a model of recording electrodes in it is shown in Figure 1B (upper panel). To locate the electrodes after the experiment, we scanned a CT image (Parameters: FOV = 8 cm, Voltage = 110kv, Current = 0.1mA) for each monkey and aligned the CT image with the MRI image (Figure 1B, bottom).

METHOD DETAILS

Temporal Order Judgment Task

Monkeys were trained to perform a temporal order judgment task based on naturalistic videos. In each trial, the monkey initiated a trial by pressing a colored rectangle in the center of the screen (0.3 ml water). Following a blank screen (range from 1s to 3s), an 8s video was presented. After a short period of delay (no delay or 3.6s delay), two frames extracted from the video were displayed bilaterally on the screen for TOJ. The monkey was required to choose the frame that was shown earlier in the video to get a reward (1.2 ml water), and the target frame remained alone for 4s as positive feedback. If the monkey made an error, the screen would be blanked for 4s with no reward.

The temporal distances between the two frames were fixed in all trials (85 frames). To control for temporal similarity [61],we included two delayed conditions. In the immediate condition, the two probe frames were extracted from the first half of the video (i.e., 5th vs 90th frame), with zero retention delay between encoding and retrieval. In the delayed condition, the two probe frames were extracted from the second half of the video (i.e., 95th vs 180th frame), with a retention delay of 3.6 s.

We collected 42 daily sessions of data from Jupiter, and 21 sessions from Mercury. In the first stage, we completed 24 sessions of Jupiter and 3 sessions of Mercury. 30 different videos were used in each block, and each video was shown once corresponding to two different conditions (i.e., immediate vs. delayed conditions). Each session contained 6 to 10 blocks (Jupiter: 8.417±1.100, Mercury: 7.333±1.528) depending on the monkey's performance. In the second stage, we completed 18 sessions for both Jupiter and Mercury. 15 different videos were used twice with each video shown once for immediate and delayed conditions in each block. Each session contained 3 to 10 blocks (Jupiter: 8.444±1.723, Mercury: 5.667±1.138). In both stages, the same set of videos were randomized across different blocks and reused across three consecutive days.

Electrophysiology

We recorded 676 single neurons in 63 sessions from 2 macaque monkeys (401 cells from 42 sessions in Jupiter and 275 cells from 21 sessions in Mercury). We used 32-channel semi-chronic Microdrive systems (SC-32, Gray Matter System) with 1.5 mm inter-electrode spacing, connected to the data acquisition system (Smart box, NeuroNexus Technologies, Inc., USA). Neural activity was amplified and stored for offline sorting (Offline Sorter, Plexon). On average, 9.548±2.276 and 13.095±4.265 neurons per session were recorded simultaneously for Jupiter and Mercury, respectively. We treated clusters identified from the same electrodes on different days as separate neurons.

QUANTIFICATION AND STATISTICAL ANALYSIS

Behavioral Data Analysis

Trials with RT longer than 10 s (1.71%) were excluded from the analyses.

Spike Detection and Sorting

The raw signal was filtered with a low-cut digital filter (4-pole Butterworth filter, 250 Hz), and we set 3 standard deviations as the threshold of detecting spikes. After removing high amplitude artifacts, we sorted spikes with the Standard E-M algorithm in Offline Sorter (Plexon). We used several criteria to quantify spike sorting quality and to select well-isolated single units. Criteria that we used were signal-to-noise ratio, L-ratio, and isolation distance [62] (Figure S1).

GLM fitting

We fit every single cell with Poisson GLM using *stepwiseglm* function in MATLAB. To exclude all the potential effects caused by behavior or other event period, we fit the model with following variables: block number within one session, reaction time, response correctness (correct vs incorrect), conditions (immediate vs delayed condition), touch side (left vs right), and average firing rate in each event of the paradigm including pre-trial fixation, encoding period, delay period, TOJ period, feedback (reward vs punishment) and ITI period. The variables with an adjusted R^2 smaller than 0.005 were excluded from the model, and variables with an adjusted R^2 larger than 0.01were included. The firing rate of each event period was calculated as the mean firing rate during that event. TOJ cell was defined as cells that include TOJ period in the model.

Mahalanobis Distance Index

We first calculated the mean firing rate of each neuron recorded in that session for Video watching and TOJ period trial by trial. Next, the squared Mahalanobis distance of each trial was calculated with the MATLAB function '*mahal*'. Since the number of neurons are different from session to session, we divided the Mahalanobis distance with two times of cell number in that session for comparison across sessions.

SPIKE-distance

The SPIKE-distance measures the relative spike timing between spike trains normalized to local firing rates. For each spike of each pair of spike trains recorded in the same session, we calculated the time difference between the nearest following spikes of two spike trains and the time difference between the nearest preceding spikes of two spike trains. These distances are interpolated between spikes using all time differences to the previous spike and the following spike. The instantaneous weighted spike time difference for a spike train can be determined via the interpolation from one difference to the next. For each session, we averaged over all pairs of neurons to acquire the averaged SPIKE-distance value for each time point. The pairwise SPIKE-distance profile is subsequently obtained by averaging the weighted spike time differences, normalized to the local firing rate average, and weighted each profile by the instantaneous firing rates of the two spike trains. Averaging over all pairwise SPIKE-profiles results in a multivariate SPIKE-profile. We obtained the SPIKE-distance value for each pair of two spike trains and represented all pairwise averaged dissimilarity profiles in a n x n matrix (n denotes the number of neurons recorded in one session). Calculation of SPIKE-distance and pairwise SPIKE-distance for all neurons in the same

session was done with SPIKY [63]. For interpretation, the smaller the value is, the more similar the spike trains are, and thus there is a higher synchrony between spike trains.

Temporal Context Cell Fitting

We analyzed the spike data of two monkeys via a maximum likelihood estimation script run in MATHEMATICA 12.1. In order to determine whether a neuron had a time-locked response to the onset of video clips, we calculated model fits of nested models for each neuron across all trials considering the time from the onset of image presentation to 8s after image presentation. The nested models contain three models.

1) The constant model, $F_{const}(t; a_0) = a_0$, which is only determined by a single parameter a_0 that predicted the average firing rate at each time t.

2) The Gaussian model, $M_{gauss}(t; a_0, a_1, \mu, \sigma) = a_0 + a_1 \frac{1}{\sqrt{2\pi\sigma}} e^{\frac{-(t-\mu)^2}{2\sigma^2}}$.

3) The ex-Gaussian model, $M_{ex-gauss}(t; a_0, a_1, \sigma, \mu, \tau) = a_0 + a_1 \int_{-\infty}^{\infty} e^{-\frac{(t-\mu)^2}{2\sigma^2}} e^{-\frac{t}{\tau}} dt$, which is represented by the convolution of a Gaussian function with an exponentially decaying function.

Since the ex-Gaussian model degrade into either a Gaussian function (as $\tau \to 0$) or an exponential function starting at μ (as $\sigma \to 0$), this model performs well in describing both temporal context cells and time cells. As such, neurons which are better fitted by the ex-Gaussian model are considered responsive. We selected neurons with three criteria: 1) were better fitted by the ex-Gaussian model at the 0.05 level, 2) changed their firing rate by at least 2 Hz, 3) reached a firing rate of at least 4 Hz. Fits of nested models for each neuron are analyzed via a likelihood ratio test.

Linear Discriminant Analysis

To decode temporal information from the population activity of mPPC neurons, we followed the analysis method of the previous study [26]. We trained the classifier with even trials and tested the temporal information in odd trials. For each 8 s video in each trial, we took 250 ms as the time bin and divided the whole encoding period into 32 bins. For each bin of each trial, the firing rate of all neurons in that session was calculated. One element of testing data or training data is the averaged firing rate of each time bin for each trial across all neurons. Due to the number of trials that range from session to session, we randomly select 200 trials when the number of trials in one session is larger than 200. While the number of trials is fewer than 200, we bootstrapped it to 200 trials. In this case, some trials would have been selected twice. LDA was implemented using the MATLAB function "classify", and we used linear estimation for our dataset. To access the actual error in each classification, we calculated the absolute temporal distance between the actual time and decoded time in each time bin and got the averaged value across all the time bins. Besides, due to the error in the first period of the video being lower than the rest of the video for two monkeys (Figure S3), we repeat the same analysis when removing the time bins from the earlier part of the video at the step of 0.5 s. To quantify the success of LDA, we permuted time labels of training data, and repeated the analysis 1000 times. The classifier's performance was considered

significantly better than chance if fewer than 10 of 1000 permutations gave a better result than the real data.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online.

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AUTHOR CONTRIBUTIONS

Conceptualization, SZ, SCK; methodology, SZ, WL, ZJ, MK, SCK; investigation, SZ, WL, MK; formal analysis, SZ, CW; visualization, SZ, CW; writing – original draft, SZ, CW, SCK; writing – review & editing, SZ, SCK; supervision, SCK; funding acquisition, SCK.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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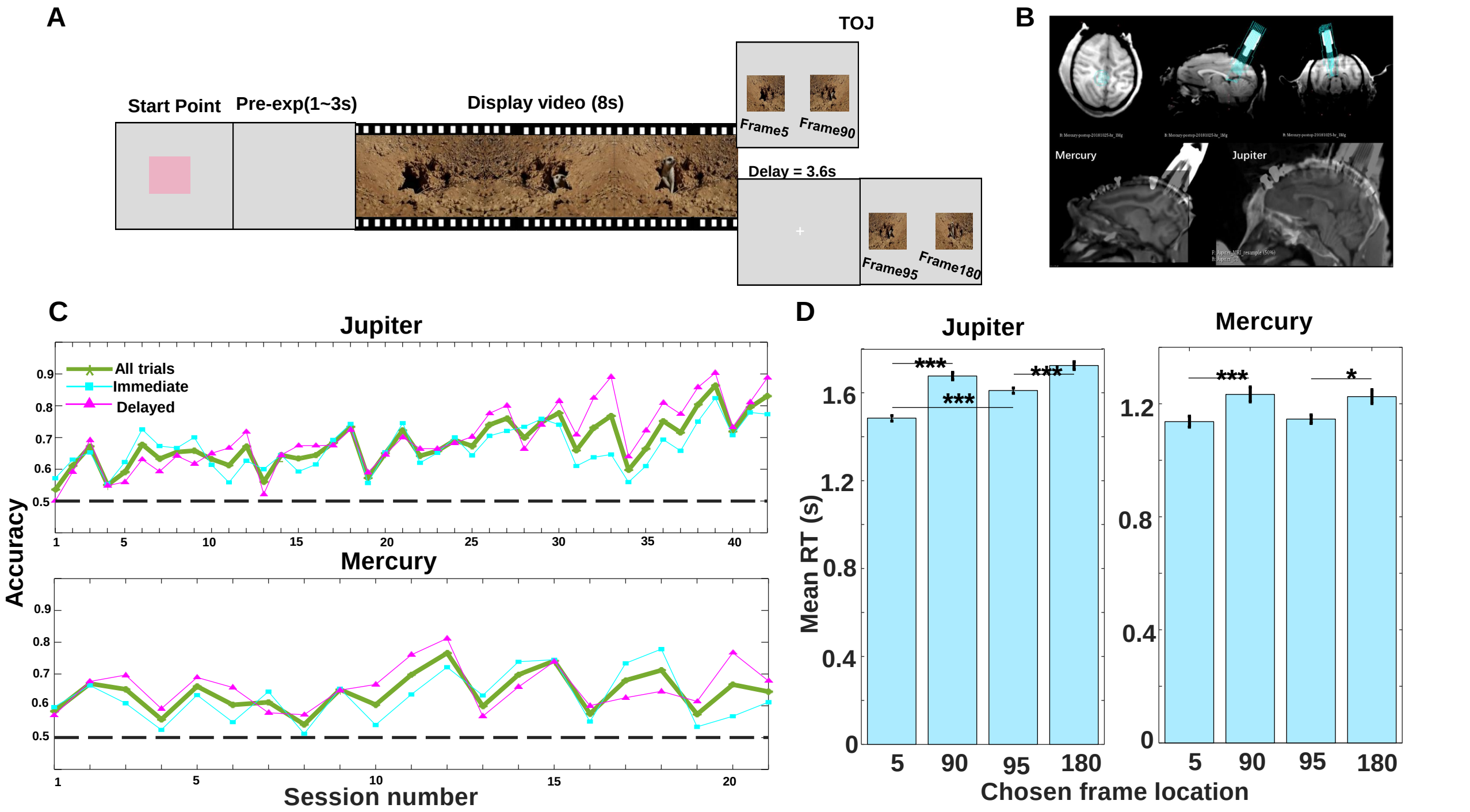
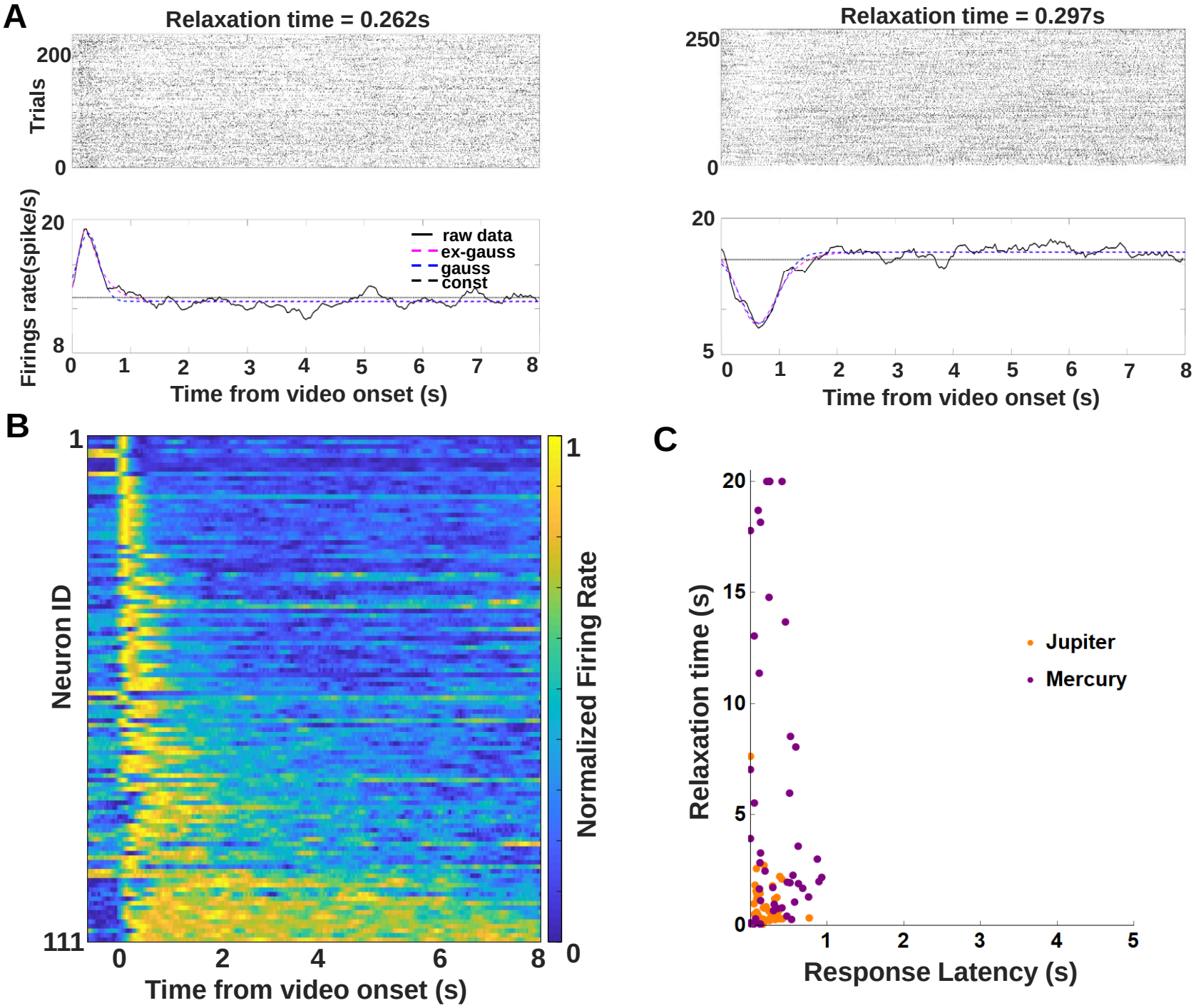
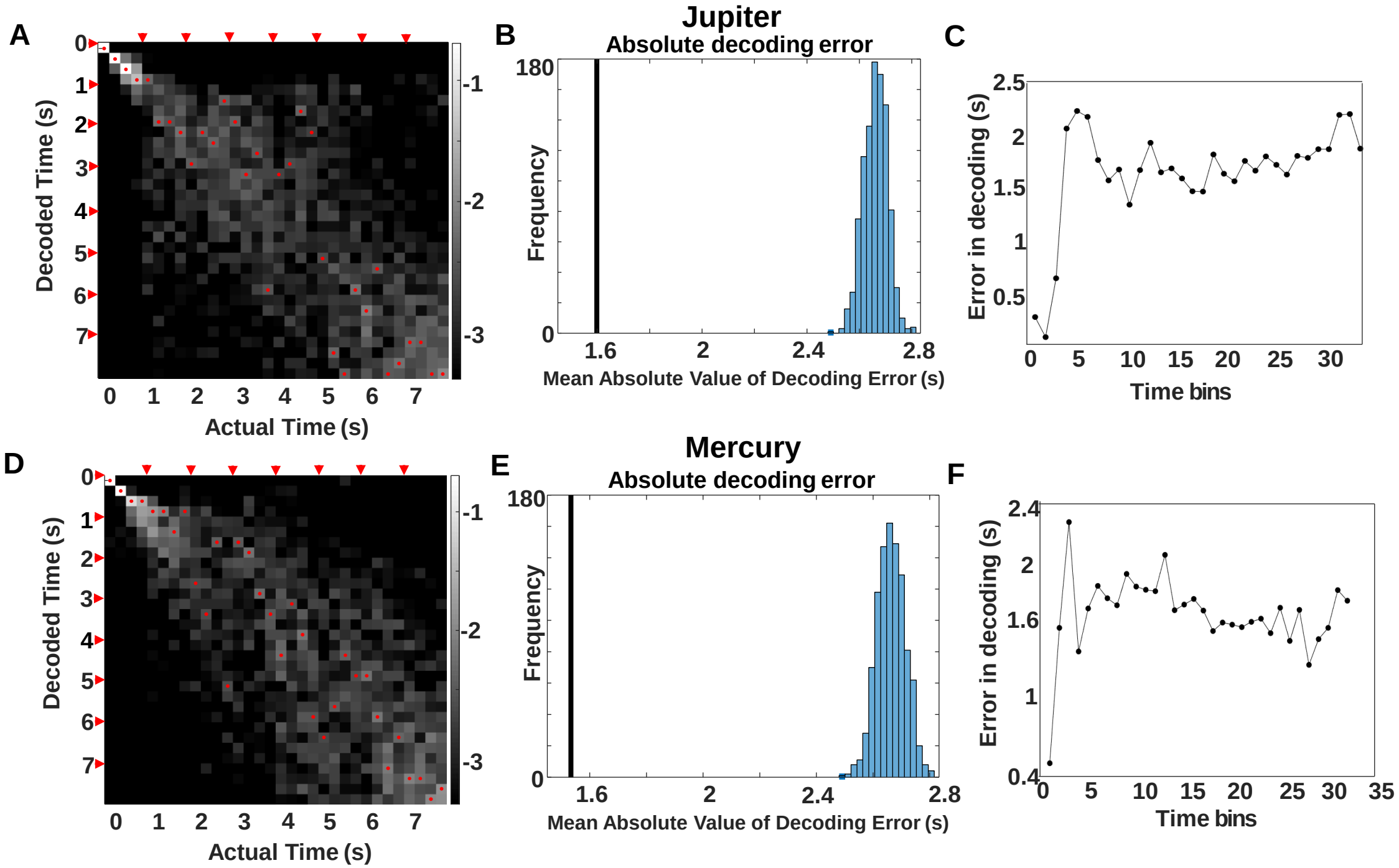
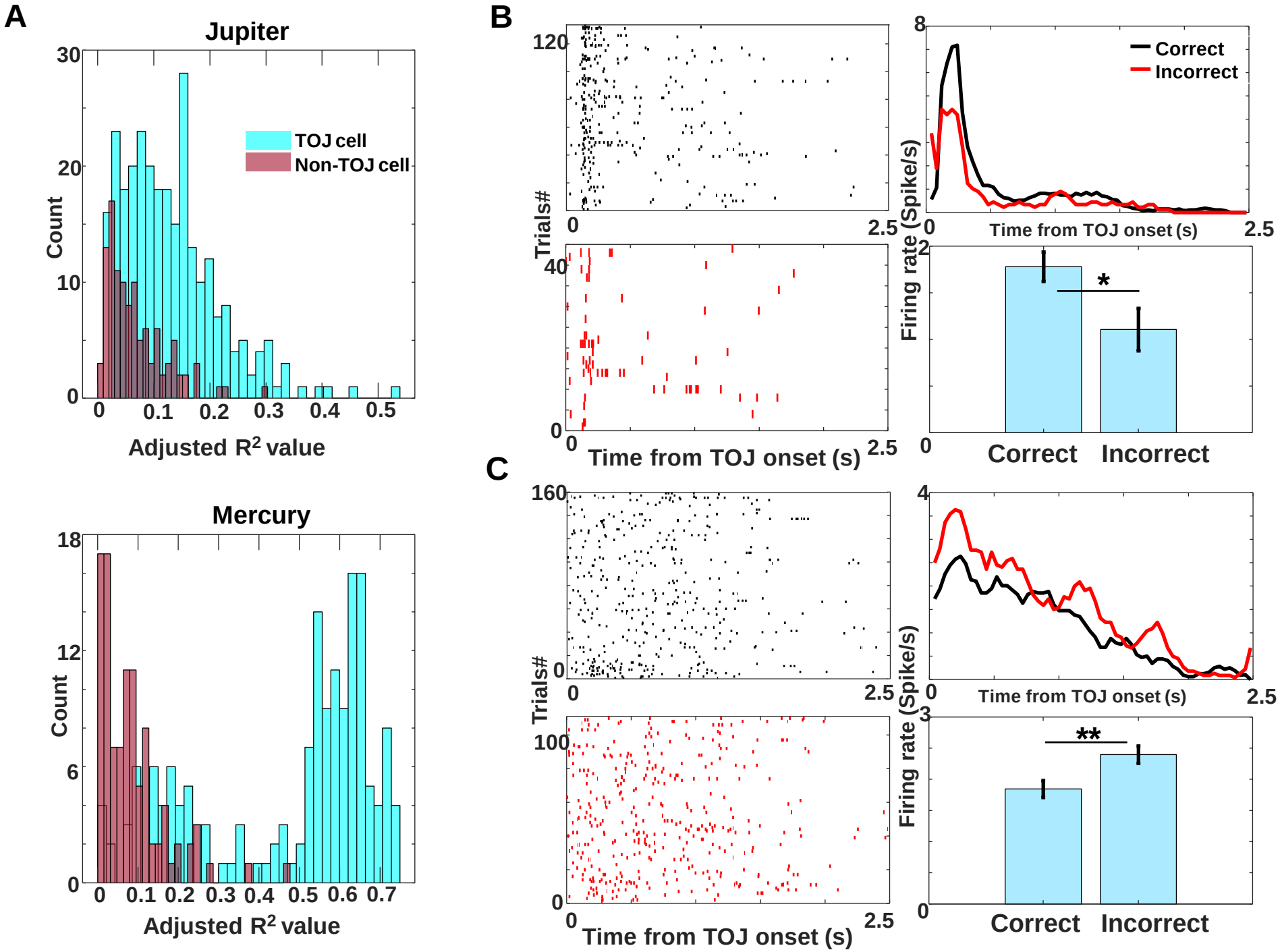
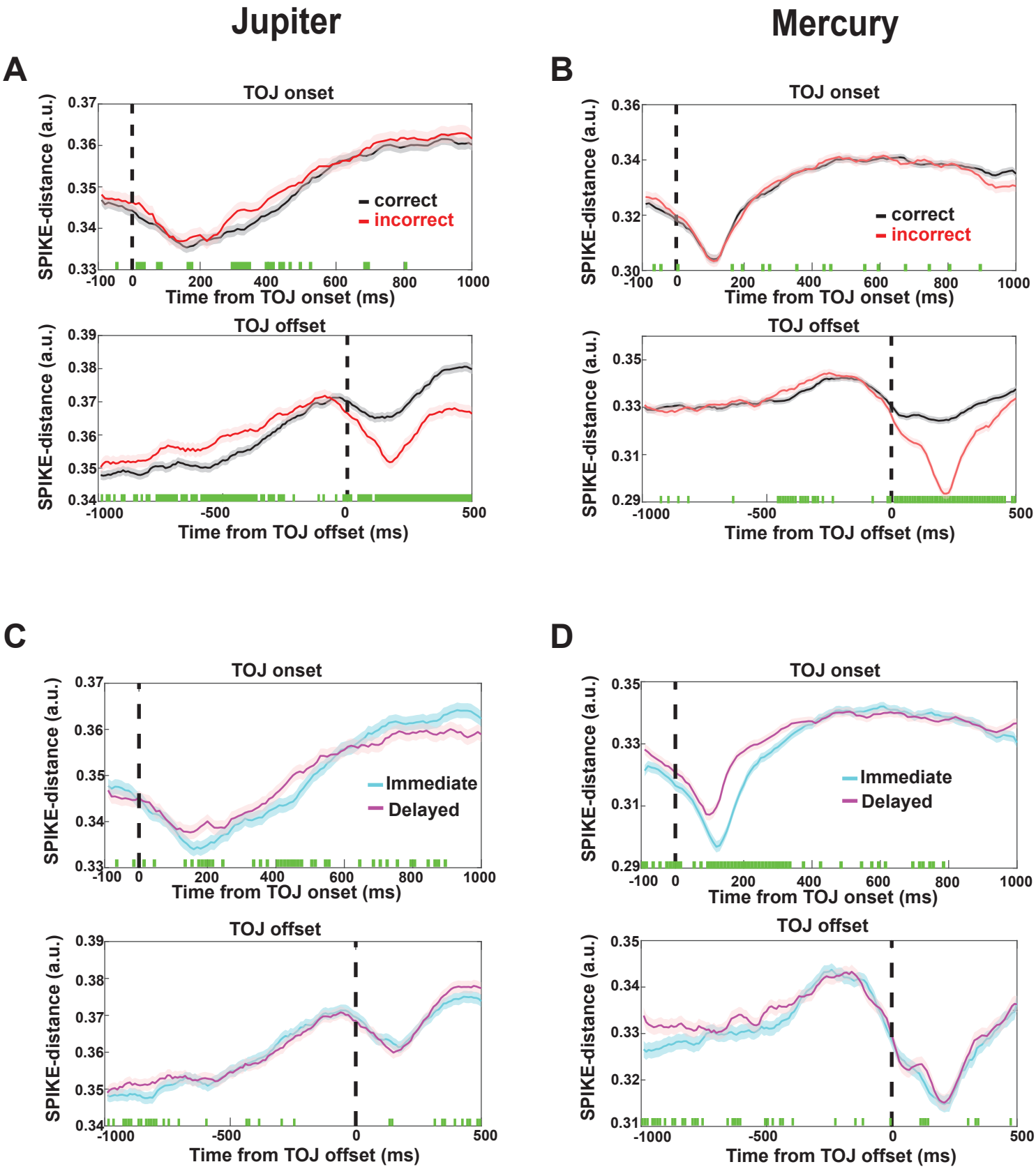
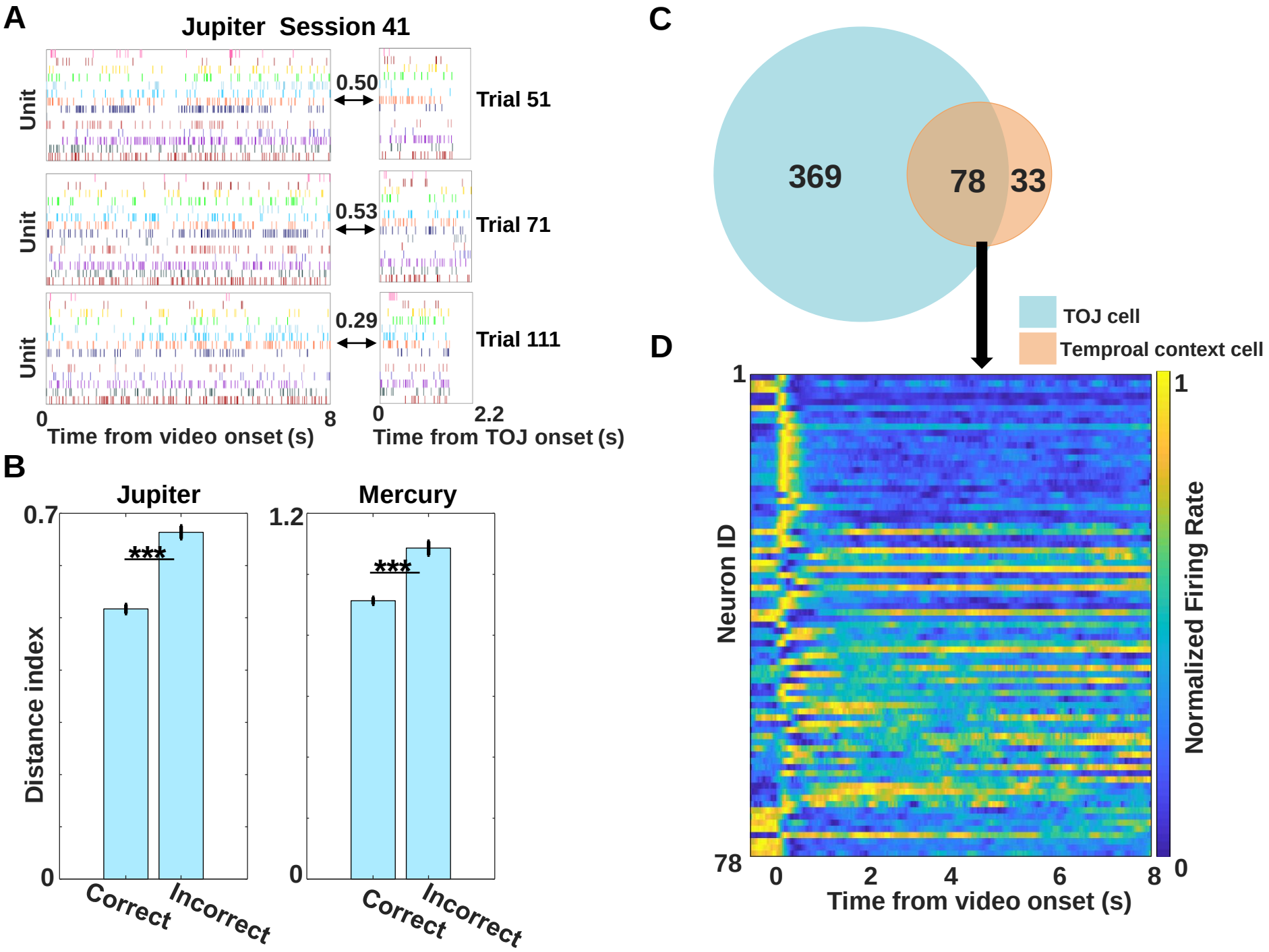

A
TOJ
Start Point
Pre-exp(1~3s)
Display video (8s)
Frame5
Frame90
Delay = 3.6s
Frame95
Frame180
B
Mercury
Jupiter
C
Jupiter
All trials
Immediate
Delayed
Accuracy
Mercury
Session number
D
Jupiter
Mercury
Mean RT (s)
Chosen frame location

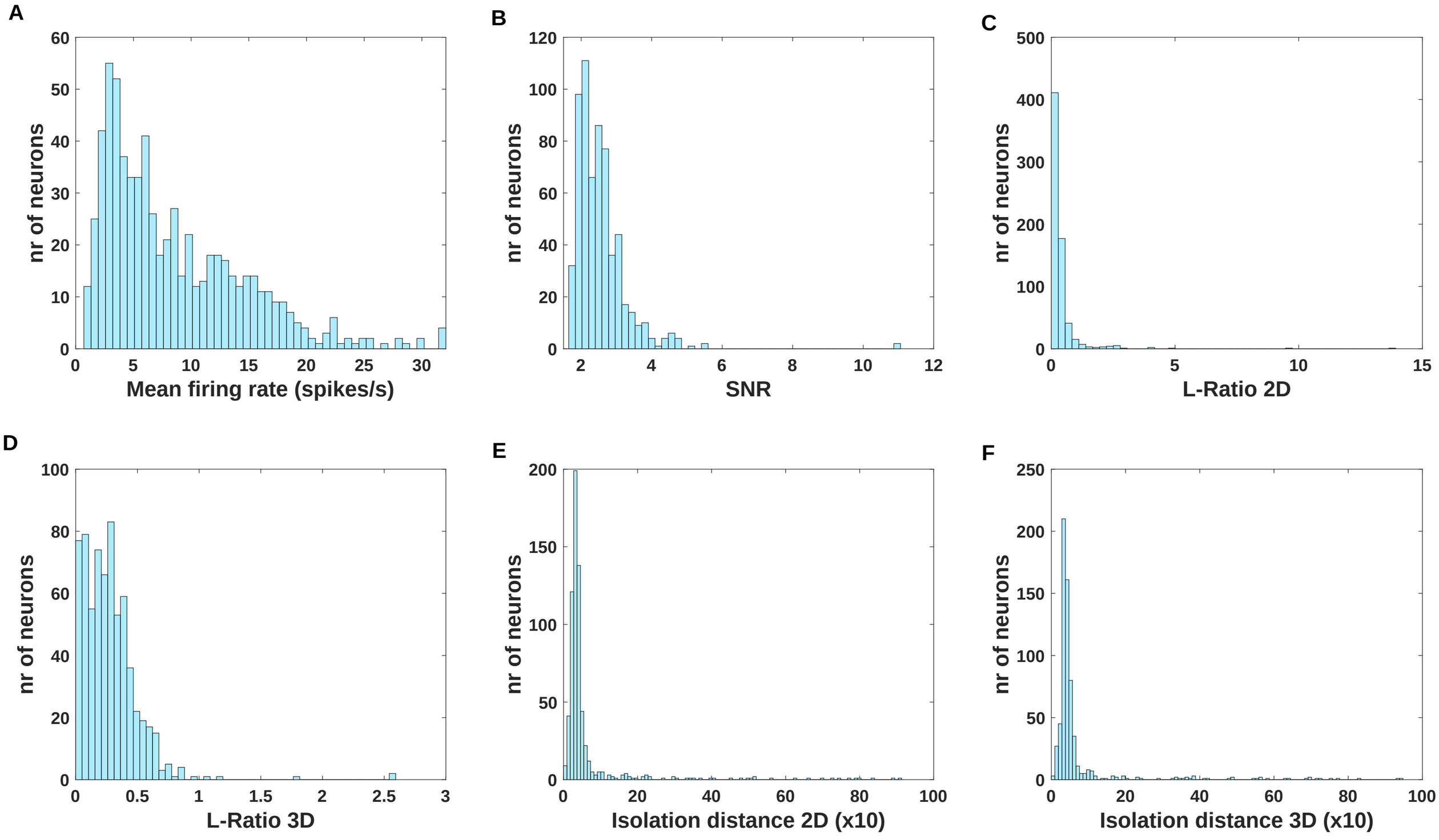

A
Relaxation time = 0.262s
Trials
200
0
Firings rate(spike/s)
20
8
raw data
ex-gauss
gauss
const
0 1 2 3 4 5 6 7 8
Time from video onset (s)
Relaxation time = 0.297s
250
0
20
5
0 1 2 3 4 5 6 7 8
Time from video onset (s)
B
Neuron ID
1
111
0 2 4 6 8
Time from video onset (s)
Normalized Firing Rate
1
0
C
Relaxation time (s)
20
15
10
5
0
1 2 3 4 5
Response Latency (s)
Jupiter
Mercury

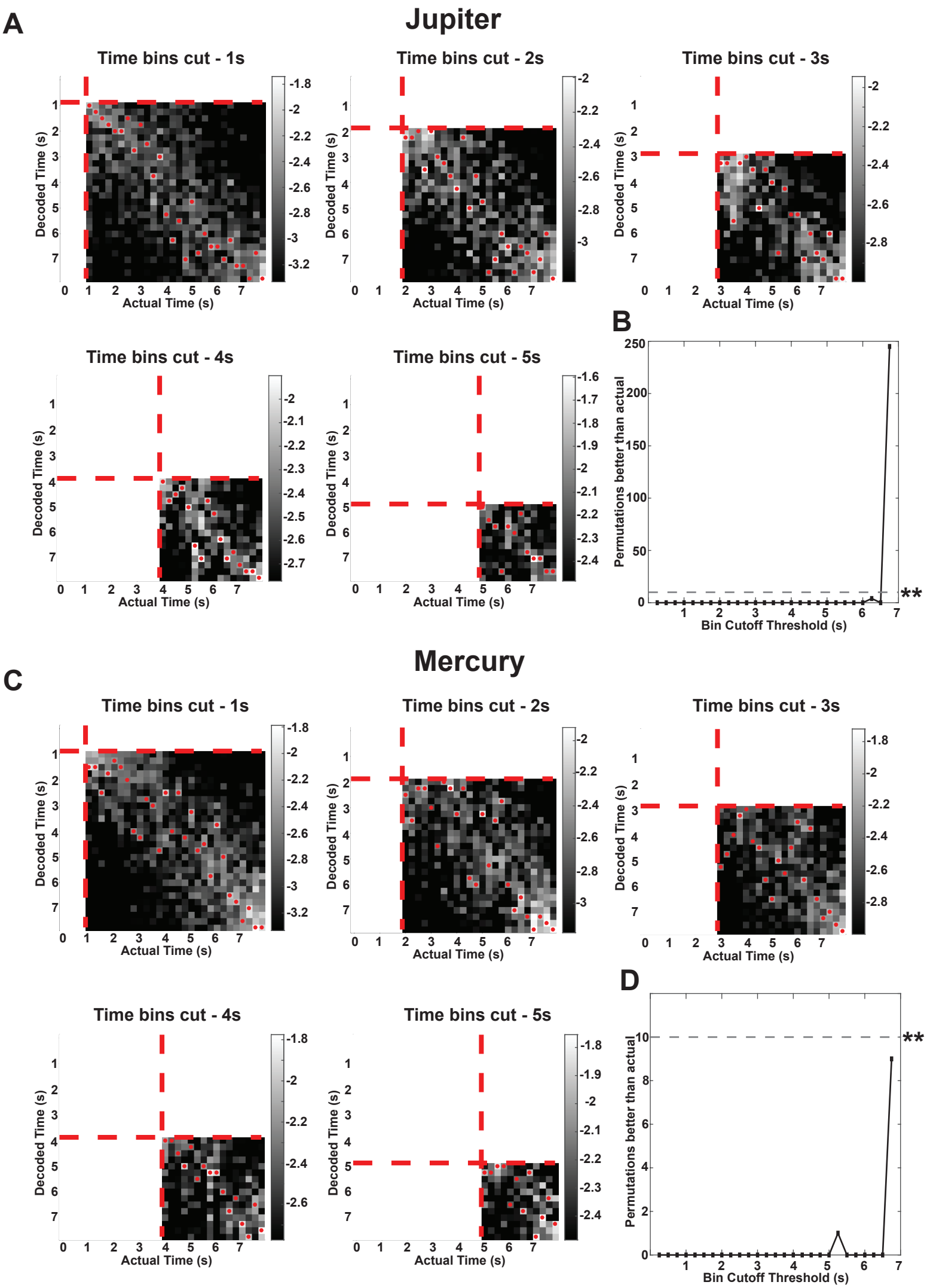

Jupiter
A
B
C
Absolute decoding error
Decoded Time (s)
Actual Time (s)
Frequency
Mean Absolute Value of Decoding Error (s)
Error in decoding (s)
Time bins
Mercury
D
E
F
Absolute decoding error
Decoded Time (s)
Actual Time (s)
Frequency
Mean Absolute Value of Decoding Error (s)
Error in decoding (s)
Time bins


A
Jupiter
TOJ cell
Non-TOJ cell
Count
Adjusted R2 value
Mercury
B
Trials#
Time from TOJ onset (s)
Correct
Incorrect
Firing rate (Spike/s)
C


Jupiter
Mercury
A
B
C
D
TOJ onset
TOJ offset
SPIKE-distance (a.u.)
Time from TOJ onset (ms)
Time from TOJ offset (ms)
correct
incorrect
Immediate
Delayed


A
Jupiter Session 41
Unit
0.50
Trial 51
Unit
0.53
Trial 71
Unit
0.29
Trial 111
0
8
Time from video onset (s)
0
2.2
Time from TOJ onset (s)
B
Jupiter
Mercury
0.7
1.2
***
***
Distance index
0
0
Correct
Incorrect
Correct
Incorrect
C
369
78
33
TOJ cell
Temproal context cell
D
1
78
Neuron ID
0
2
4
6
8
Time from video onset (s)
1
0
Normalized Firing Rate


A
nr of neurons
Mean firing rate (spikes/s)
B
nr of neurons
SNR
C
nr of neurons
L-Ratio 2D
D
nr of neurons
L-Ratio 3D
E
nr of neurons
Isolation distance 2D (x10)
F
nr of neurons
Isolation distance 3D (x10)


A
Jupiter
Time bins cut - 1s
Time bins cut - 2s
Time bins cut - 3s
Time bins cut - 4s
Time bins cut - 5s
Decoded Time (s)
Actual Time (s)
B
Permutations better than actual
Bin Cutoff Threshold (s)
**
C
Mercury
Time bins cut - 1s
Time bins cut - 2s
Time bins cut - 3s
Time bins cut - 4s
Time bins cut - 5s
Decoded Time (s)
Actual Time (s)
D
Permutations better than actual
Bin Cutoff Threshold (s)
**