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## Supplemental Information

# The Basal Ganglia Do Not Select Reach Targets but Control the Urgency of Commitment

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## Supplemental Information

**Table S1 (related to Table 1): Motor discharges in the globus pallidus** (count and percentage of modulated /correlated cells)

| | Monkey S | | Monkey Z | |
|---|---|---|---|---|
| **Movement-related**† | | | | |
| Modulated | 19/34 | 56% | 35/61 | 57% |
| *Increase* | 10/19 | 53% | 23/35 | 66% |
| *Decrease* | 10/19 | 53% | 16/35 | 46% |
| **Spatial tuning**† | | | | |
| Tuned | 11/34 | 32% | 25/61 | 41% |
| **Reaching kinematics**‡ | | | | |
| Reach peak velocity | | | | |
| *Slow block* | 6/41 | 15% | 19/66 | 29% |
| *Fast block* | 8/35 | 23% | 15/59 | 25% |
| Reach amplitude | | | | |
| *Slow block* | 4/41 | 10% | 16/66 | 24% |
| *Fast block* | 5/35 | 14% | 13/59 | 22% |
| Reach duration | | | | |
| *Slow block* | 4/41 | 10% | 19/66 | 29% |
| *Fast block* | 7/35 | 20% | 23/59 | 39% |
| Reach vigor | | | | |
| *Slow block* | 4/41 | 10% | 23/66 | 35% |
| *Fast block* | 6/35 | 17% | 21/59 | 36% |

†: Measured in the delayed reach task (95 cells tested)
‡: Measured in the tokens task (107 cells tested in the slow block, 94 in the fast block)

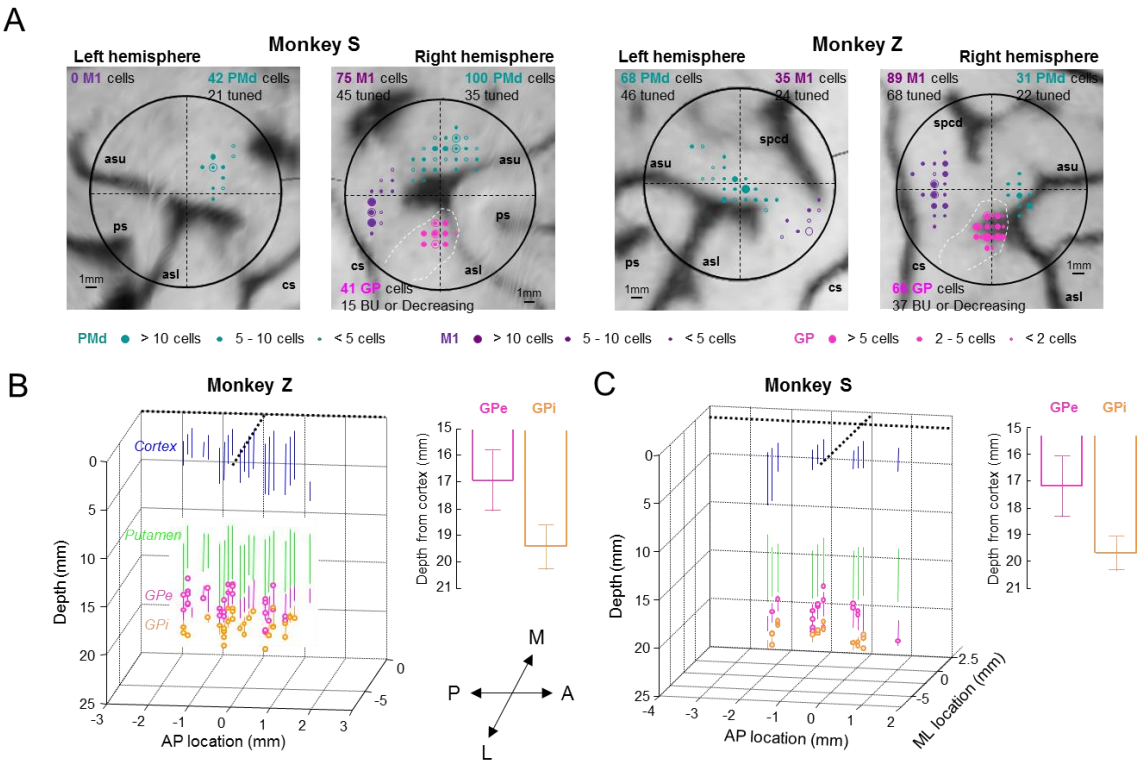


**Figure S1: Recording sites (related to STAR Methods)**

**A.** Reconstructed images of the brain surface from anatomical MRI scans. Large circles represent the location of the recording chambers. Colored circles represent the location of the recording sites, classified as PMd (blue-green), M1 (violet) or GP (magenta, including both GPe and GPi) based on anatomical location. White dotted lines illustrate the extent of the globus pallidus (top view) estimated from the 3D MRI reconstruction. **B.** 3D plot of electrode tracks during GP recording sessions in monkey Z. Each colored vertical line illustrates the average depths at which PMv (blue), putamen (green), GPe (magenta) and GPi (orange) cells were observed during the descent of the electrode in a given antero-posterior (AP) and medio-lateral (ML) location. For each track location, colored circles mark where GPe (magenta) and GPi (orange) cells were recorded. Here, 0mm corresponds to the depth at which the first cell was observed in the cortex. The inset in the top right part of the plot shows the average (± SD) depth (in relation to the first cortical cell) of all cells recorded in GPe and GPi. **C.** Same as *B* for GP recording sessions in monkey S.

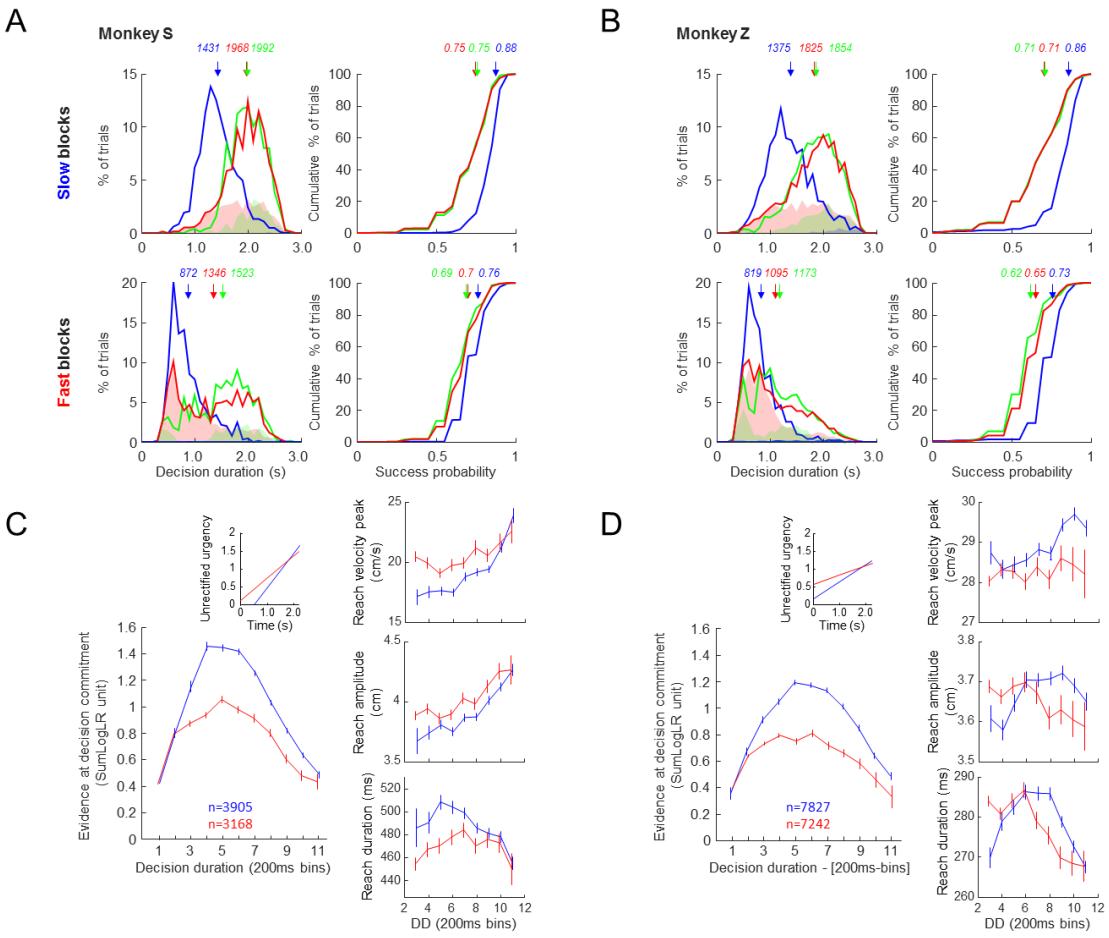


**Figure S2: Behavioral data (related to Figure 1)**

**A.** Distribution of monkey S decision durations (left panels) and success probabilities (right panels) in easy (blue), ambiguous (green) and misleading (red) trials (correct choices and errors) executed either in the slow (top panels) or in the fast block (bottom panels). In the decision durations plots, the colored and shaded areas illustrate distributions of error trials. Colored arrows and numbers indicate the mean of each distribution. Data corresponds to sessions in which GP neurons were being recorded **B.** Same as *A* for behavioral data collected in monkey Z. Both monkeys made decisions significantly earlier in easy than in ambiguous or misleading trials (WMW-test, $p<0.01$). They also made decisions at a significantly lower level of success probability in ambiguous and misleading trials than in easy trials (WMW-test, $p<0.05$). We also found that the block condition strongly influenced monkeys' strategy in the tokens task. Both animals were hastier and less accurate in the fast condition compared to the slow condition (WMW-test, $p<0.05$ for all the tested comparisons, compare top and bottom panels), in agreement with the notion that saving time usually occurs at the expense of accuracy (speed-accuracy trade-off). **C.** *Left panel*: Mean (±SE) of the evidence available at commitment (calculated as the SumLogLR) as a function of decision duration (computed in 200ms bins) during slow (blue) and fast (red) blocks performed by monkey S. Data corresponds to sessions in which GP neurons were recorded. Inset shows the urgency functions derived by Thura et al. (2014) for each

monkey and each block. *Top right panel*: Mean (±SE) of monkey S peak velocity of arm movements across trials binned according to decision duration in 200ms bins, in the slow (blue) and fast (red) block. Trials with decision duration below 600ms are excluded from the analysis (3% of trials in the slow block, 27% in the fast block). *Middle right panel*: Mean (±SE) of monkey S's movement amplitude as a function of decision duration and block conditions in the same trials. *Bottom right panel*: Mean (±SE) of monkey S's total movement duration in the same trials and conditions. **D.** Same as *C* for behavioral data collected in Monkey Z. We computed, for each monkey and each block type, the average of the available sensory evidence for the chosen target at the time of commitment as a function of decision duration (Cisek et al., 2009). Left panels in *C* and *D* shows that, for both animals and in both blocks, the average level of sensory evidence at the time of commitment first increases and then (after about 900ms) decreases as a function of decision duration (ANCOVA for decisions made after the 2$^{nd}$ token jump, Effect of decision duration, $F=1411.1$, $p<0.0001$ for monkey S; $F = 590$, $p<0.0001$ for monkey Z). Although the average evidence function is non-monotonic, it can be explained with a simple, linearly-growing urgency signal, as shown by Thura et al. (2014). In brief, as urgency grows the evidence needed to reach commitment gradually decreases, producing the late part of the function. The early, rising part can simply be explained by random noise that pushes neural activity to commitment even while the evidence is low.

We found that, for both monkeys, the evidence at commitment was significantly higher during slow blocks than fast blocks (ANCOVA for decisions made after the 2$^{nd}$ token jump, Effect of block, $F=678.6$, $p<0.0001$ for monkey S; $F = 800.9$, $p<0.0001$ for monkey Z). This implies a higher level of urgency in the fast block, as expected based on the faster decisions observed in this condition. We also noted that the difference of available sensory evidence at decision time between blocks tends to vanish as time is passing during a trial (Block*Duration, $F=295.5$, $p<0.0001$ for monkey S; $F = 105.5$, $p<0.0001$ for monkey Z). This is probably because as time is elapsing, the amount of time monkeys can save in the fast condition diminishes, reducing the motivation to behave differently in the two conditions. Overall, the data suggests that monkeys adjust their level of urgency between the two SAT conditions, raising it when they are more willing to guess in fast blocks and lowering it to be more conservative in slow blocks. Because we previously proposed that the same urgency signal invigorates both decisions and movements (see Thura et al., 2014), we here again analysed reaching parameters as a function of decision duration and block condition. In a smaller sample size of trials (only trials during GP recording sessions), we found the same quantitative results as described previously on a larger dataset. Both monkeys adjusted and tended to reduce their movement duration as a function of decision duration (ANCOVA for decisions made after the 2$^{nd}$ token jump, Effect of duration, $F=12.6$, $p=0.0004$ for monkey S; $F = 54.7$, $p<0.0001$ for monkey Z), and movement duration was shorter in the fast condition compared to the slow condition (Effect of block, $F=46.7$, $p<0.0001$ for monkey S; $F = 4.7$, $p=0.029$ for monkey Z). To achieve this shortening, the two monkeys adopted different strategies: Monkey S adjusted his vigor level (velocity and amplitude of movements) in such a way that suggests an influence of the urgency signal estimated based on animal's behavior during decision-making (Block*Duration effect on reach velocity, $F=36.6$, $p<0.0001$; Block*Duration effect on reach amplitude, $F=10.06$, $p=0.0015$). Monkey Z also increased his vigor level in the slow condition (Block*decision duration effect on movement speed, $F=10.4$, $p=0.0012$) but also

tended to mostly reduce his movement amplitudes in the fast block for the longest decisions (Block*decision duration effect on movement amplitude, F=14.3, p=0.0001).

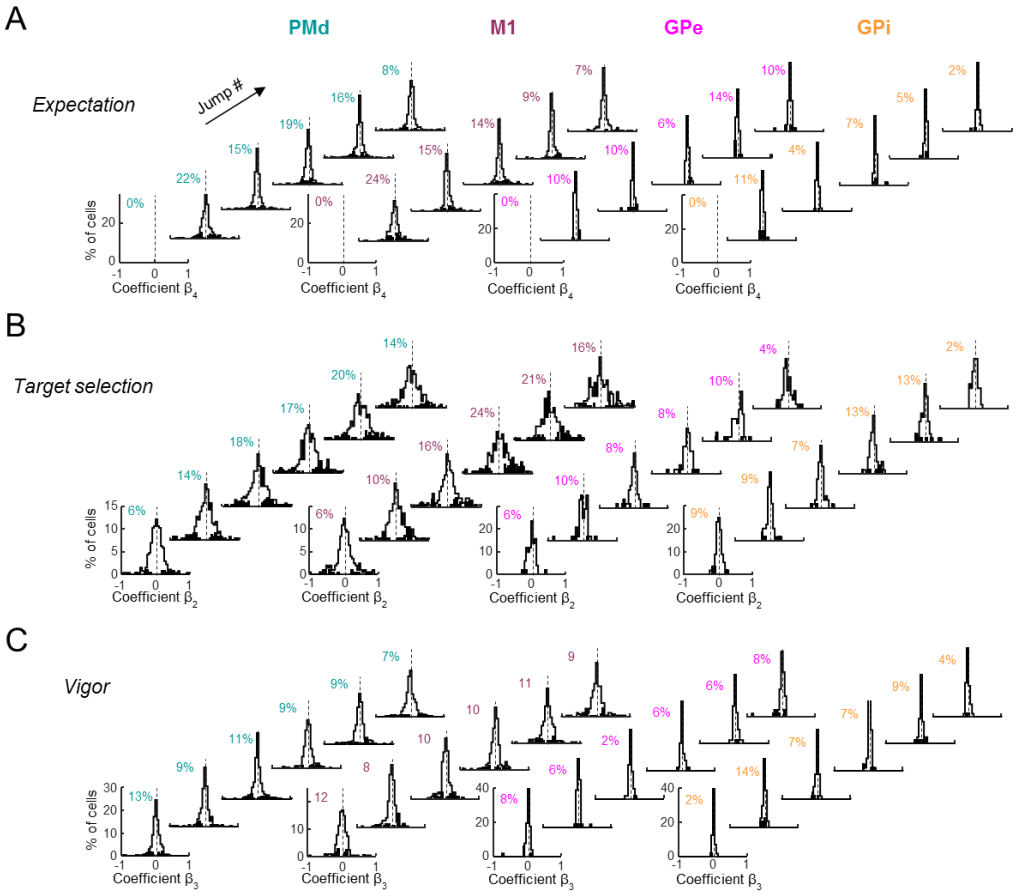


**Figure S3: Effect of movement vigor, chosen target and jump 'expectation' on cortical and GP activity (related to Figure 2)**

**A.** Distributions of the multiple linear regression model $\beta_4$ coefficients (equation 2) computed in PMd, M1, GPe and GPi after each of the first 6 token jumps. The $\beta_4$ coefficient corresponds to the effect of seeing a token jump into the target that currently has received more tokens at a given time. Black bars illustrate cases for which the "expectation" regressor has a significant effect on neural response according to the linear regression model ($H_0$: $\beta_4 = 0$ rejected, $p<0.05$). Numbers on top of each plot indicate the percentage of significantly modulated cells. **B.** Same as *A* for $\beta_2$ coefficients in the linear model, i.e. the effect of the target chosen by the monkey at the end of the trial on the neural response. **C.** Same as *A* for $\beta_3$ coefficients in the linear model, i.e. the effect of movement vigor on the neural response.

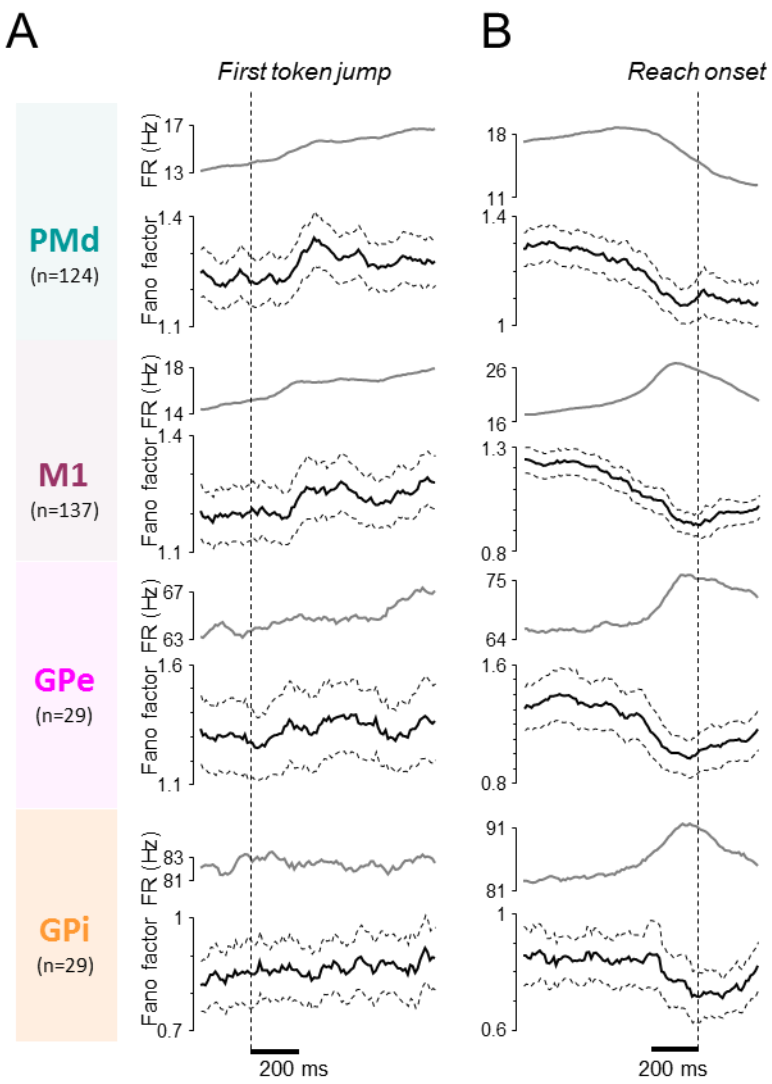


**Figure S4: Variability of cortical and GP activity during deliberation and before movement onset (related to Figure 3)**

**A.** Averaged neural firing rate (gray curve) and across-trial variability (±SE, black curves) of the tuned PMd (n=124, top row), M1 (n=137, second row), GPe (n=29, third row) and GPi (n=29, bottom row) neurons aligned on the first token jump in the tokens task. Data include all trials from the slow block with decision duration above 800ms. The variability is computed as the Fano factor, i.e. the spike count variance divided by the spike count mean (see Churchland et al., 2010). Counts are made in a 75ms sliding window over the time course of the tested epoch (from 300ms before to 800ms after the first token jump). **B.** Same as *A* with activity aligned on movement onset, with an epoch of analysis extending from 800ms before to 300ms after movement onset.

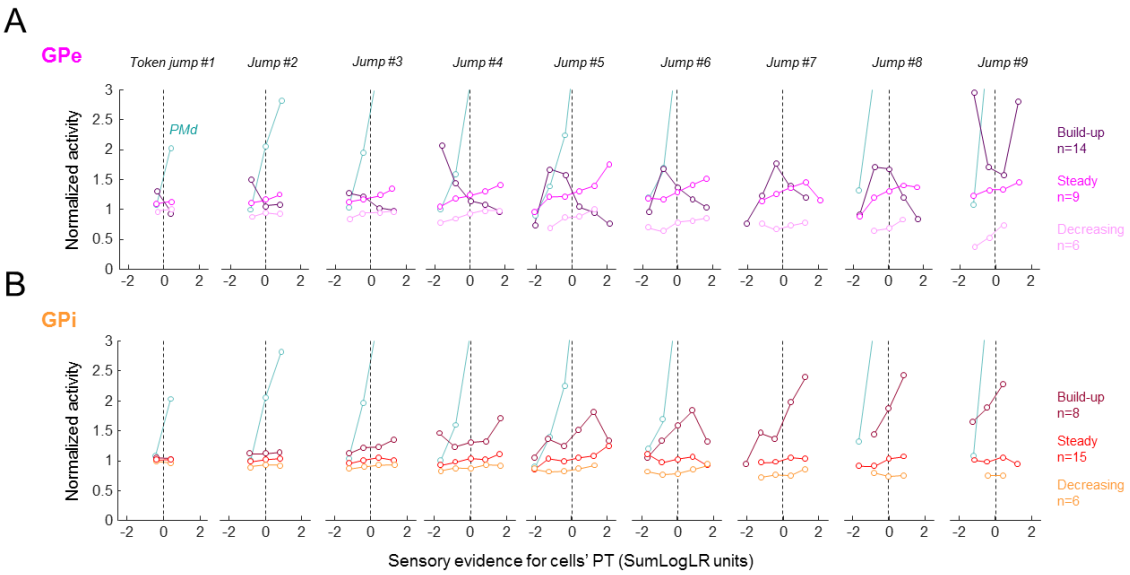


**Figure S5: Influence of sensory evidence on build-up, steady and decreasing GP cells (related to Figure 5)**

**A.** Each panel illustrates the correlation between build-up (dark magenta), steady (magenta) and decreasing (light magenta) GPe neurons activity and sensory evidence (calculated as SumLogLR with respect to cells' PT), 200ms after each of the first 9 token jumps. Activity is normalized against baseline and spikes recorded after decision commitment are discarded (same convention as in Figure 3E). Correlation between PMd neurons and sensory evidence is illustrated for comparison in green **B.** Same as *A* for a population of build-up (brown-red), steady (orange) and decreasing (light orange) GPi cells.

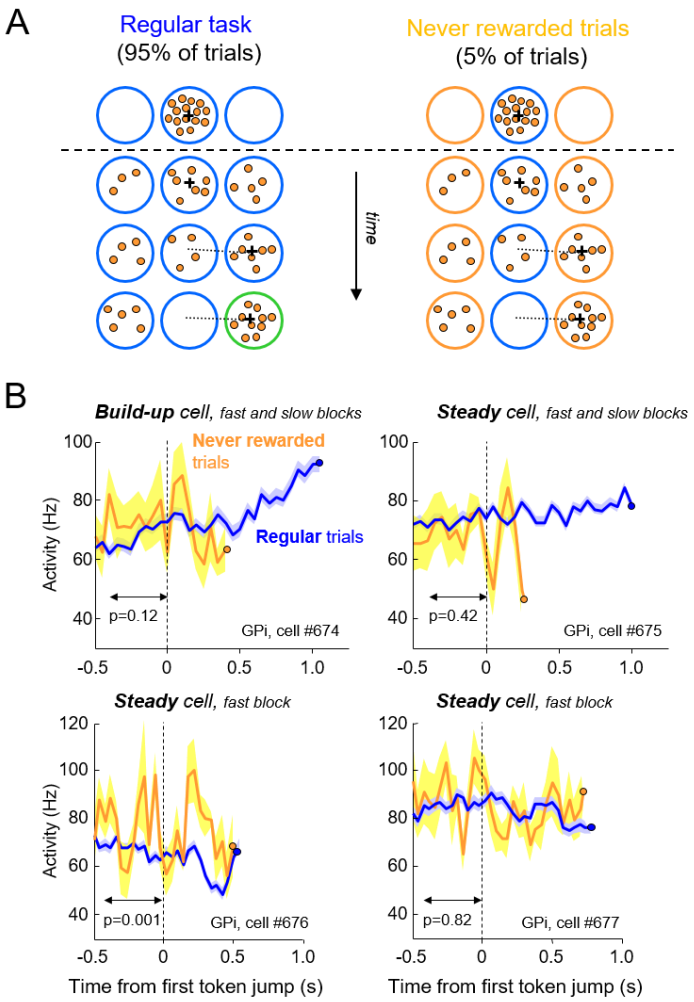


**Figure S6: GPi activity and reward anticipation (related to Figure 5)**

**A.** Time course of a regular tokens task trial (left) and a "never rewarded" trial. Both trial types are identical except that in never rewarded trials (about 5% of trials), the lateral circles (targets) are orange, indicating to the monkey that in this trial, he won't receive any reward regardless of his choice (correct or error), but must still complete the trial to move on to the next one. **B.** Four examples of GPi cells tested in the "never-rewarded" trials interleaved with regular trials in the tokens task. See Methods for the criteria used to classify cells as "build-up" or "steady" cells. Neural response to never-rewarded trials is illustrated in orange whereas the response to regular trials is shown in blue. In each of these cells, activity is aligned on the first token jump, combined for both targets and truncated after decision commitment (squares). Depending on the cell, activity is also combined across blocks of trials (fast and slow, two top panels). Horizontal black arrows illustrate the time period (-400ms/0ms relative to the first token jump) for which a WMW test assessing the difference of firing rate between the two conditions was performed. Numbers below the arrows correspond to the p-values. Note that no cells exhibited a decrease in baseline activity, as would be expected if they reflected reward anticipation, and one (bottom left) showed a significant increase.